A comparison of biodegradation caused by Teredinidae (Mollusca:Bivalvia), Limnoriidae (Crustacea:Isopoda), and *C.terebans* (Crustacea:Amphipoda) across 4 shipwreck sites in the English Channel

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Abstract:

The need to protect underwater cultural heritage from biodegradation is paramount, however with many sites needing funding and support, it is hard to prioritise, thus the ability to identify high risk sites is crucial to ensure resources are best placed. In doing so a clear understanding of environmental conditions acting upon a site and abundance and composition of species present is essential to this identification. Therefore, the aim of this study was to assess the rate of biodegradation on four underwater cultural heritage sites in different marine environments by placing a series of wooden test panels in direct contact with the exposed structure on the sites. Upon recovery, test panels were photographed, X-rayed, and wood boring and sessile fouling species were identified and counted. The damage attributed to each species was recorded with CAD software. Results indicated a significant difference between sites, with HMS *Invincible* having the highest abundance of marine wood borers and the highest rate of surface area and volume degradation; whilst vestigial evidence of marine wood borers was found on the *London*, it would appear the environmental conditions had significantly impeded their survival. The study indicated further factors such as sediment type and coverage, availability of wood and the proximity of other colonised sites were also determining factors controlling the abundance of marine wood borers and the rate of biodegradation.

Keywords: Biodegradation, underwater cultural heritage, Lyrodus pedicellatus, Teredo navalis, Limnoria

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1.0 Introduction

For centuries, timber has been a focal material for shipbuilding, with its wide spread availability, natural hardiness and workable qualities (Eaton & Hale 1993); furthermore, numerous timber species are available, dependant on region, with elm, oak and pine most commonly used in European shipbuilding until mid-19th century (Couper 2000, McGrail 2001). England has derived a prominent relationship with the sea, building global trade networks and developing a strong naval force (Smith 2009, Vego 2016); as such, the English Channel has an extensive history of trade, transport and warfare reflected in the many underwater cultural heritage (UCH) sites along the coastline (Pater 2007). However, many of these wooden UCH sites are at risk of degradation by marine wood borers within the Amphipoda, Isopoda and Myodia (Borges 2014).

Teredinidae (Mollusca:Bivalvia), consist of 68 species (Voight 2015), with *Teredo navalis* and *Lyrodus pedicellatus* commonly found within English waters. Both are protandrous hermaphrodites; born as males, they later transition into females, and spawn free swimming larvae into the water column (Coe 1943, Lane 1959, Appelqvist & Havenhand 2016). *T.navalis* remains in the water column for 17-34 days before settlement, and are capable of travelling large distances and inhabiting a range of sites (Appelqvist et al 2015, Lippert et al 2017). *L.pedicellatus* retains their eggs until they are further along in their developmental stage (Wurzinger-Mayer et al 2014); due to this, *L.pedicellatus* remain in the water column for 24-48 hours, making them more likely to recolonise the same site compared to *T.navalis* (Borges et al 2010). This method aids in minimising larval mortality and the risk of being carried to unfavourable environments. After settlement, Teredinidae larvae metamorphose, and the development of a shell covered in serrated teeth enables them to bore, and tunnel formation begins (Quayle 1992, Lippert et al 2017). Within these tunnels, Teredinidae grow and consume wood for the duration of their lives, however, survival and growth of Teredinidae is linked to the availability of wood, thus rapid settlement and growth are vital to survival (Cragg et al 2009, Macintosh et al 2014) but detrimental to the wood they live within.

Limnoria (Crustacea: Isopoda) have a worldwide distribution with *L.lignorum, L.quadripunctata* and *L.tripunctata* abundant in English waters (Jones 1963). *Limnoria* give birth to a small number of live young (Eltringham & Hockley 1961, Quayle 1992), providing extended parental care, and enabling a low mortality rate (Mohr 1959, Thiel 2003). The young rapidly mature and begin to bore secondary burrows away from the maternal burrow, forming interconnecting burrows under the surface of the wood (Mohr 1959, Thiel 2003). Due to their limited swimming capabilities *Limnoria* can only migrate over short distances, and as a result develop large, rapidly growing aggregations that aggressively attack wood until depletion (Mohr 1959, Thiel 2003). The burrows destroy the wood's original surface area, and as weakened wood breaks away, *Limnoria* burrow deeper, eventually depleting the wood volume.

The marine amphipod, *Chelura terebans*, is found in association with *Limnoria* and has a preference for pre-softened wood, in which they bore to enlarge *Limnoria* burrows (Poore et al 2002, Green Etxabe 2013). Independently, *C.terebans* is not a major concern, mainly because they rely on wood for shelter rather than nutrition (Green Etxabe 2013); however the concerning factor is *C.terebans'* ability to worsen the damage made by *Limnoria*.

Teredinidae, *Limnoria* and *C.terebans* are affected by differences in the marine environment, thus varying environmental conditions can affect the rate of biodegradation (Florian et al 1977). Temperature and salinity are dominant factors affecting distribution, growth and reproduction of marine wood borers (Eltringham & Hockley 1961, Nair & Saraswathy 1971, Appelqvist et al 2015). *T.navalis* has a broad tolerance to temperature and salinity, allowing a long spawning season in English waters and the ability to settle in diverse habitats; whilst *L.pedicellatus* shares similar temperature tolerances, their salinity tolerance limits them to marine sites (Table 1), (Nair & Saraswathy 1971, Borges et al 2010, Paalvast and Van de Velde 2011, Borges 2014, Borges et al 2014 a, Appelqvist et al 2015, Appelqvist & Havenhand 2016, Lippert et al 2017, Fofonoff et al 2018 a). *L.lignorum* are suited to salinities in brackish and marine waters, and a preference for cooler temperatures allows them to reproduce throughout most of the year, with a wide distribution across the UK; *L.quadripunctata* and *L.tripunctata* are restricted to warmer marine waters, and thus limited to the south of England (Table 1), (Jones 1963, Borges et al 2010, Borges et al 2014 b, Fofonoff et al 2018 b). Temperature preferences may also affect depth distribution; *Limnoria* are abundant in shallow waters, living in the intertidal range to 30 m (Cookson 1991, Shalaeva 2012), however, the depth distribution for *C.terebans* is unknown, but it is active in warmer shallow waters down to at least 12 m (unpublished results). Similarly, *T.navalis* has a depth range down to 150 m but is more abundant and destructive in shallower waters down to 20 m (Bernard et al 1993, Elam 2009). Thus, most shallow sites lying within optimum temperature ranges, such as the majority of wooden protected wreck sites along the south coast of England (Historic England 2018), are at risk of biodegradation.

Dissolved oxygen is a dominant factor controlling the distribution and survival of marine wood borers (Menzies et al 1963, Anderson & Reish 1967, Eriksen et al 2014), and should be considered alongside sediment type and coverage, which can create anoxic conditions and affect larval settlement; hence, studies have successfully trialled various reburial methods of wooden UCH, aiming to produce anoxic conditions for *in situ* preservation (Gregory 1998, Palma 2005, Curci 2006, Manders 2006, Bjordal & Nilsson 2008, Palma & Parham 2009, Eriksen et al 2014). Other factors for consideration are the availability of wood and competition for space, particularly with sessile fouling species (Weiss 1948, Quayle 1992), water movements, which although may aid larval settlement and burrow oxygenation, can also have opposing effects (Doochin & Smith 1951), and the wood type and direction of cut (Eriksen et al 2016). Marine wood borers have a preference to non-durable wood (Sivrikaya et al 2009) , but studies have shown Teredinidae prefer wood cut on the radial plane, which is common on clinker built boats such as the Skuldelev ships, Bremen cog and *Grace Deiu,* where timber was radially split for construction (Crumlin-Pedersen 1984, Litwin 1998, Childs 2009, Eriksen et al 2016).

New UCH sites are found each year, and with minimal funds and resources for excavation, there has been a shift in the way UCH is managed (Manders et al 2009, 180, Eriksen et al

2015), hence European and international conventions (Valetta Treaty 1992, ICOMOS Charter 1996, UNESCO Convention 2001) now recommend that long term *in situ* preservation of UCH should be considered the first option over excavation. In line with these policies, a number of projects (MoSS 2003, Wreck Protect (Manders 2011), SASMAP (Manders & Gregory 2015 a, b) have developed methods for monitoring and *in situ* preservation in different environments; additionally, some of these projects have highlighted that severity of attack by marine wood borers is dependent on environmental conditions. Thus, for *in situ* protection to work, an understanding of the behaviour of marine boring species in different environments is needed, with a strong understanding of site conditions to ensure conducive recommendations for the most constructive and cost effective methods. Furthermore, with numerous UCH sites requiring support, and limited time and funding, this information could allow for easy identification of high risk sites, so support and funding can be prioritised without risking further degradation. Therefore, the aim of this study was to assess the rate of biodegradation in relation to species abundance across four sites with varying environmental conditions; this would allow for the identification of key conditions which affect the rate of biodegradation and the identification of potentially high risk sites in comparison to low risk sites.

2.0 Method

Three test panels of elm (*Ulmus.sp.)*, oak (*Quercus.sp.)* and pine (*P.sylvestris)* (timber identification pers comm), (total nine panels) sized 200x75x25 mm, in accordance with EN275 (1992) standards, were placed across four shipwreck sites in the English Channel (Fig.1). Test panels were cut tangentially using a band saw; however, archaeological wood would have been prepared differently with axes, adzes and hand saws and would be radially split for clinker built boats or tangentially sawn for carvel built boats (Crumlin-Pedersen 1984, Childs 2009). Nonetheless, deployment of these test panels has given an indication into biodegradation on these sites and the species present.

2.1 Test Panel Deployment

Test panels were deployed on the *London* and HMS *Invincible* for six months throughout the summer of 2016; there was a limited window for deployment and retrieval on the other sites, thus test panels were deployed for four months on Poole Cannon Site and five months on the West Bay Wreck (Table 2). To ensure the test panels were faced with the same environmental conditions as the archaeological timber on the sites, they were tied in direct contact with the wreck's exposed timber structure, on the seabed, with polypropylene rope and cable ties. Where possible a handheld YSI Pro 30 conductivity and salinity meter was used to collect temperature and salinity data at seabed level, where not possible, temperatures were recorded using the diver's computer (Table 2).

2.2 Laboratory Analysis

Each test panel was observed using a Brunel BMDZ Stereomicroscope with a magnification of x 7.5 to x 45, and every specimen on the surface of the test panel was recorded. Although fouling species were not the primary focus of the study, some sessile fouling species reduce available space and damage the timber surface (Bowens 2009); thus, species that posed these issues were recorded. *Limnoria* were identified using identification keys and illustrations provided by Menzies (1957) and Castello (2011), and sex and maturity level were observed. Teredinidae were identified by the number of boreholes; it was recorded if the borehole was a result of a failed larval settlement through the presence of an empty, spherical depression or if the specimen had been successful and a calcareous structure or tunnel present; from this a percentage of successful settlement was calculated. On completion of X-Radiography, Teredinidae pallets were collected and identified using identification keys and illustrations created by Turner (1966 & 1971). When pallets were identified, the tunnel length of the individual was recorded by pushing flexi wire through the tunnel.

2.2.1 Surface Area Analysis

Surface area loss attributed to *Limnoria*, *C.terebans* and fouling species was assessed using a CAD software programme, Rhino 3D 5.0, developed by Robert McNeel & Associates. The Rhino 3D 5.0 software contains multiple functions which records 2D and 3D measurements with high accuracy. Test panels were photographed on each face using a quadropod; the images were then uploaded to the software and scaled. Using the 'interpolated curve' command function, the outline of each ventilation hole, individual tunnel, group of tunnels or fouling species could be traced (Fig.2); by applying the 'patch' command function, the software fits a patch surface between the traced outline made by the 'interpolated curve' and calculates the surface area (Fig.2). Percentage of surface area loss attributed to *Limnoria* and *C.terebans* was aligned with the EN275 grading system (1992), (Fig.3), allowing results to be comparable to other studies (Camidge 2009, Palma & Parham 2009, Borges 2014, Palanti et al 2015). Teredinidae damage that could be identified by the X-Ray image, was graded using EN275 (1992), (Fig.3), however, as heavy colonisation on the test panels made it hard to identify individual tunnels and determine an accurate percentage using Rhino 3D 5.0, a visual estimate was given using a 1 cm^2 Perspex grid. The grid was placed over the X-ray image, and areas of colonisation could be shaded and an estimated percentage of surface area calculated.

2.2.2 X-Radiography and Volume Analysis

To confirm the abundance of Teredinidae and calculate the volume of wood lost, test panels were X-rayed using a Gulmay HS 225kV Hi Stability X-ray system for the *London* and HMS *Invincible* test panels and a Faxitron 43804N for the Poole Cannon Site and West Bay test panels. Each X-ray was completed at 50–70 kV over 90 –120 seconds, depending on the test panel density; 180x240 mm AGFA Structurix D4 film was used with a Fe filter plate on one side. Teredinidae specimens were identified on the X-ray by the presence of its shell and calcareous lining, both of which are highly apparent via X-ray (Fig.4). Where possible the length and volume of each specimen were determined using Rhino 3D 5.0; by using the 'interpolated curve' command function, a line could be placed lengthways down the centre of each specimen's tunnel, from which the software calculates the tunnel length (Fig.4), (Knight 2018). Using the 'pipe' command function, several radiuses were extended from the central line; this allows the software to create a 3D mesh replica of the shipworm tunnel and calculates the tunnel volume (Fig.4), (Knight 2018). Due to difficulties in the identification of individual tunnels on HMS *Invincible*, this method was only employed on X-rays from Poole Cannon Site.

2.2.3 Statistical Analysis

Statistical analysis was completed using the statistical software programme, SPSS, through which, one-way ANOVA tests were completed to identify if a significant difference was present between two or more independent groups. The level of significance was set at p=0.05. The use of one way ANOVA tests allows for multiple variables such as mean abundance of *Limnoria* on pine test panels across all 4 sites to be compared. When these factors were tested using one way ANOVA, a result of statistical significance was produced; if the result was p=<0.05, a statistically significant difference was present. When a statistically significant difference was identified, the null hypothesis was rejected and Tukey HSD post hoc comparison tests were completed to identify which groups within the sample group were significantly different. For example, the Tukey HSD post hoc results highlighted that, when testing the difference in mean abundance of *Limnoria* on pine test panels, a highly significant difference was evident between the *London* and HMS *Invincible,* with a result less than p=0.05 (Table 3), suggesting the abundance of *Limnoria* between these sites is very different; whilst no significant difference was identified between the *London* and West Bay wreck with a result greater than p=0.05, suggesting little to no variation in mean abundance of *Limnoria* between these sites (Table 3).

3.0 Results

Upon recovery test panels from the *London* were covered in silt sediment, with some shallow, singular *Limnoria* burrows (Fig. 4) and very minimal surface coverage from fouling species. Test panels from HMS *Invincible* and Poole Cannon Site were recovered with no sediment coverage and varying levels of biodegradation, with the presence of *Limnoria, C.terebans* and Teredinidae in large numbers, and some surface coverage from fouling species (Fig.5). Unfortunately, oak test panels from Poole Cannon Site were lost during the study and no results are reflected below. Test panels from the West Bay Wreck were covered in a thin layer of sediment, however, no damage from wood borers was evident and the presence of fouling species was pronounced (Fig.5).

3.1 Limnoria and C.terebans

Whilst no evidence of *Limnoria* or *C.terebans* was found on West Bay, vestigial evidence of *Limnoria* was found on the *London* (Table 4). During one way ANOVA tests the mean abundance of *Limnoria* and *C.terebans* across all sites produced highly significant results (with the exception of the mean abundance of *C.terebans* on elm test panels, from which no specimens were collected) (Table 4); thus Tukey HSD post hoc comparisons were completed to identify which sites were significantly different from each other (Table 3). Tukey HSD post hoc comparison results comparing mean abundance of *Limnoria* and *C.terebans* on the *London* and West Bay sites produced a p value >0.05 (Table 3), indicating no significant differences between the *London* and West Bay, hence mean abundance of *Limnoria* and *C.terebans* on these sites shows little to no variation. Similar results showing no significant differences or little to no variation were observed when analysing mean abundance of *C.terebans* on pine test panels, between Poole Cannon Site, and the *London* and West Bay sites (Table 3). However, relationships between the remaining sites were significant with a p value <0.05, suggesting the abundance of *Limnoria* and *C.terebans* on test panels across these sites varies significantly (Table 3), with the highest mean abundance of *Limnoria* and *C.terebans* identified on HMS *Invincible* for all test panels (Table 4). *L.quadripunctata* was identified on every test panel on HMS *Invincible* however, no *C.terebans* was collected from elm test panels and a clear preference to pine was observed (Table 4, Fig.6). On Poole Cannon Site, *L.quadripunctata* were the dominant species found on all test panels, whilst *L.lignorum*, were only found on pine making up 9% of the species composition (Fig.6). Further comparisons between test panel material and mean abundance of *Limnoria* and *C.terebans* using one way ANOVA tests indicated another highly significant difference with a p value <0.05 (Table 5); Tukey HSD Post hoc comparisons identified a significant difference in species abundance between pine and elm test panels, with both *Limnoria* (p=0.035) and *C.terebans* (p=0.002) showing a clear preference for pine.

3.2 Teredinidae

No Teredinidae presence was identified on any of the test panels from West Bay, and whilst boreholes were identified on all test panels from the *London*, these appeared to be failed larval attempts (Table 4). One way ANOVA tests were completed to understand if the mean total number of boreholes or mean number of successful boreholes varied based on test panel material, however no significant differences were observed (Table 5) and so the null hypothesis was accepted and no further analysis completed. However, one way ANOVA tests did highlight a significant difference when comparing the mean number of total boreholes and mean number of successful boreholes between the different sites, on pine test panels (Table 4). As a result Tukey HSD post hoc comparisons were completed and identified a significant difference in both the mean number of total boreholes and mean number of successful boreholes on pine test panels between HMS *Invincible* and the other sites, with p values less than 0.05 (Table 3); thus indicating the mean number of total boreholes and mean number of successful boreholes on HMS *Invincible* was greatly different to the other sites. HMS *Invincible* had the highest mean number of total boreholes and mean number of successful specimens, with a settlement success rate of 61% on pine test panels, 55% on oak and 13% on elm (Table 4). Both *L.pedicellatus* and *T.navalis* were identified on HMS *Invincible*, however, the *T.navalis* specimens identified were less than 5 mm in length, and although they were far from a rare occurrence, *L.pedicellatus* were the dominant species in size and abundance. All Teredinidae specimens identified on Poole Cannon Site were *T.navalis* and a mean settlement success of 56% was observed on pine test panels and 77% on elm (Table 4).

3.3 Severity of degradation

One way ANOVA tests were completed to analyse the relationship between mean total surface area loss on the different test panel materials over the different sites, with results showing a significant difference between the sites on pine and oak test panels with a result p=<0.05 (Table 6). Tukey HSD post hoc comparisons were completed and indicated a significant difference in mean total surface area loss on pine test panels between HMS *Invincible* and the remaining sites, however no significant differences at p=<0.05 were observed for oak test panels across any of the sites (Table 7).

Further one way ANOVA tests were completed to analyse the relationship between mean surface area loss attributed to *Limnoria* and *C.terebans,* on the different test panel materials, over the different sites, with results showing a significant difference on oak and pine test panels between sites (Table 6). Tukey HSD post hoc comparison tests indicated a significant difference on pine test panels between HMS *Invincible* and the remaining sites (Table 7); a further difference was observed on oak test panels between HMS *Invincible*, and the *London* and West Bay sites (Table 7), hence, mean surface area loss on HMS *Invincible* due to *Limnoria* and *C.terebans* is dissimilar when compared to the other sites, and likely due to the significant differences observed in the mean abundance of *Limnoria* and *C.terebans*. Finally, one way ANOVA tests were completed to analyse the relationship between mean surface area loss attributed to fouling species, on the different test panel materials, over the different sites, with results showing a significant difference on pine test panels between the sites (Table 6). Tukey HSD post hoc comparisons were completed and identified a significant difference between the *London* and West Bay sites (Table 7).

Test panels recovered from the *London* had the lowest mean total surface area loss, with fouling species responsible for less than 1%, and *Limnoria* responsible for 0.05% of the mean surface area loss on pine test panels (Table 6), (Fig.7). In contrast, HMS *Invincible* had the highest mean total surface area loss, with fouling species responsible for under 2% of mean surface area loss across all test panels; *Limnoria* and *C.terebans* were responsible for 8.02% loss on elm test panels, 13.62% on oak and 17.26% on pine (Table 6), (Fig.7). Whilst *Limnoria* and *C.terebans* were responsible for the highest percentage of mean surface area loss on pine test panels across all sites (excluding West Bay), fouling species showed a preference towards hardwoods and were responsible for the highest percentage of mean surface area loss on elm test panels across all sites (Table 6).

An average monthly rate of degradation was assigned for fair comparison due to the varying lengths of deployment between the sites. Nonetheless, results continued to follow a similar trend, though some differences were noted in that, mean surface area loss caused by fouling species on Poole Cannon Site was more prominent, with fouling coverage on elm test panels being higher than HMS *Invincible*, and surface area loss due to fouling on pine test panels was closer to HMS *Invincible* than previously recorded (Fig.8). These results were to be expected as the protruding structure and crevices on the Poole Cannon Site traps drift material, allowing rapid colonisation of fouling species and the development of a growing reef structure, whilst a large structure of this sort is less evident on HMS *Invincible*. Likewise, it was expected the West Bay results would maintain the highest fouling cover due to its location next to a well-developed rocky reef with an abundance of fouling species.

Tunnel lengths and volumes of *T.navalis* were recorded using Rhino 3D 5.0 on the Poole Cannon Site; however the method could not be accurately used on HMS *Invincible* due to heavy colonisation. Analysis of the tunnel lengths and volumes of the *T.navalis* specimens on the Poole Cannon Site showed that *T.navalis* had a longer tunnel length and volume in elm test panels when compared to pine test panels, with an average tunnel length of 3.98 mm SD 0.81 mm, and a total mean volume loss calculated at 174.46 mm^3 SD 82.79 mm^3 (0.05%) on pine test panels, and an average tunnel length of 4.56 mm SD 0.03 mm and a total mean volume loss calculated at 736.01 mm^3 SD 213.31 mm^3 (0.2%) on elm test panels. Although the analysis of individual tunnels was unsuccessful on HMS *Invincible*, it was possible to identify the longest tunnel lengths for each species, with *L.pedicellatus* reaching 30.79 mm on HMS *Invincible*, and *T.navalis* reaching 14.62 mm on Poole Cannon Site.

To quantify the damage caused by *Limnoria*, *C.terebans* and Teredinidae, and to simplify comparisons with other studies, mean surface area loss percentage was correlated to the grading system under EN275 (1992), (Fig.3). Results suggested, on Poole Cannon Site, *T.navalis, Limnoria* and *C.terebans* were equally responsible for the degradation, and all test panels were recorded at a grade 1; similarly, the damage caused by *Limnoria* was graded 1 across all test panels on the *London*, though the statistical analysis clarifies the differences here. Whilst the degradation level attributed to *L.quadripunctata* and *C.terebans* on oak and elm test panels from HMS *Invincible* were similar to other sites at grade 1, the mean degradation level on pine test panels was pronounced at 2.33; furthermore, *T.navalis* and *L.pedicellatus* were responsible for the majority of the degradation compared to *L.quadripunctata* and *C.terebans* on HMS *Invincible*.

4.0 Discussion

There are many environmental forces which lead to physical and biological degradation of wooden UCH, and as conditions vary between sites, so does the rate of degradation, thus it is paramount to identify and understand the environmental conditions on individual sites. Furthermore, the effect of physical forces such as currents and swell can lead to changes in the seabed, creating scour and sediment erosion; in turn this can destabilise a site leaving areas exposed to physical abrasion and biological attack (Muckelroy 1978, Stewart 1999, Gregory et al 2012, Manders 2017). Other factors of consideration are depth and sediment; whilst physical forces on shallow sites are more intense, leading to a greater risk of exposure and abrasion (Muckelroy 1978, Stewart 1999, Manders 2017), Muckelroy (1978) identified that the type of sediment was the *"main determining factor in the survival of archaeological material"*. Consequently, results from this study indicated sediment type was a key determining factor affecting the rate of biodegradation. Temperature, salinity and dissolved oxygen are significant parameters involved in the survival of wood borers (Eltringham & Hockley 1961, Nair & Saraswathy 1971, Appelqvist et al 2015, Appelvist & Havenhand 2016), however profiles within this study remained within optimum ranges for the survival and reproduction of these species (Table 1 & 2); thus it was evident other factors were involved in the differing rates of biodegradation and species compositions.

HMS *Invincible* lies in c.7 m on a mobile sand and shingle seabed which periodically expose areas of the wreck, however with strong water currents and sediment reduction, large areas of the wreck are becoming permanently exposed (Pascoe 2013, Pascoe & Cowan 2017, Pascoe et al 2017). Poole Cannon Site, lies at c.6 m on sand, shell and shingle sediment, but despite strong water currents and a large section of permanently exposed structure, the site appears stable and the formation of a reef occurs rapidly. In contrast, the *London* lies at c.20 m on a silt seabed, however scour pockets are increasingly evident and exposure is occurring; whilst elements of the wreck at seabed level are well preserved, elements protruding from the seabed such as the gun carriage raised in 2015, rapidly degrade from biological attack (Evans 2017). All of the above sites have an oak built structure, hence is it unlikely that any significant differences in degradation, observed on the structural timbers, is due to wood type, although in some cases, pine and elm have been used for elements such as the keel and cladding (pers comms, Pascoe et al 2017). The West Bay site lays c.12 m of water next to a rocky reef on a sand, shell, shingle and silt sediment (Palma 2010); the site has no remaining wooden structure, and instead is composed of metal remains heavily fouled with sessile fouling species (Palma 2010). Results indicated the biggest differences in species abundance and the level of degradation were often between HMS *Invincible* and Poole Cannon Site in comparison to the *London* and the West Bay site; of which depth, wood availability and sediment were among the differing factors.

4.1 Depth

The sites were located within known depth ranges for *Limnoria* and Teredinidae, who have been observed causing extensive damage to other sites within the English Channel at similar depths (Bernard et al 1993, Merrett Jones 2000, Camidge 2009, Elam 2009, Shalaeva 2012). Results from this study indicated a divide between deeper and shallower sites, however no correlation with depth was observed when other studies were considered (Merrett Jones 2000, Camidge 2009); studies completed on *Mary Rose* (18 m), *HMS Hazardous* (7 m) and HMS *Invincible* (7 m) showed extensive wood borer abundance and biodegradation; however, damage was more extensive on *Mary Rose* and HMS *Invincible* with results indicating the differences in biodegradation and species composition were due to the water quality surrounding these sites, not depth (Merrett Jones 2000). Results from *HMS Colossus* (15 m) were comparable to Poole Cannon Site and graded 1 after 5 months of exposure (Camidge 2009). Thus depth is unlikely to be a key factor controlling species abundance and biodegradation; nonetheless, due to dynamic conditions on shallow sites, depth should be considered when assessing the risk of physical factors which lead to exposure and biodegradation (Muckelroy 1978, Stewart 1999, Manders 2017).

4.2 Availability of wood and local populations

The survival of wood boring species is linked to the availability of wood hence; sites with exposed wooden remains are at risk (Cragg et al 2009, Macintosh et al 2014). However, consideration should be given to wooden UCH sites which are at risk of colonisation due to its ‘proximity’ to a colonised site, although, in this case, the term ‘proximity’ should be used rather loosely. Put simply, does the speed and direction of the tidal current allow the species on a colonised site, to travel with the current to reach and colonise another site within a limited time window. All marine wood borers have limitations in terms of the distance they are able to cover in a certain time, for example *Lyrodus pedicellatus* spends 24-48 hours in the water column before it needs to settle and metamorphose, whilst *Teredo navalis* spends up to 34 days in the water column (Borges et al 2010, Appelqvist et al 2015), hence the tidal speed and distance they cover in this time is important to understanding if other sites lie within this ‘proximity’ and therefore at risk. Furthermore, as the survival of wood borers is linked to the availability of wood, the migration to new sites allows their continued survival even once their original wood source has been depleted. The West Bay wreck was chosen as it contains no remaining wooden structure for wood borers to inhabit, and no known wooden sites were present in the direction of the tidal stream around the site, within a 24 hour window. In comparison the remaining sites have vast amounts of exposed wooden structure, and multiple colonised sites lie in the direction of several overlapping tidal streams, within a 24 hour window, making the colonisation of large populations more likely. Results indicated the availability of wood and a local infestation source was a determining factor in the abundance of marine wood borers; no evidence of wood borers were found on the West Bay wreck but a large population of *Limnoria*, *C.terbans* and Teredinidae were present on HMS *Invincible* and Poole Cannon Site (Table 4). On both HMS *Invincible* and Poole Cannon Site the spread of wood borers to local sites is facilitated through currents and drift material, and with the use of environmental cues and chemoreception, they detect the presence of wood and conspecifics, allowing them to establish new populations rapidly (Cragg et al 1999, Toth et al 2015). Hence the risk of high population abundances and rapid biodegradation is high in areas with multiple colonised sites and available exposed wood. Despite a vast wooden structure and the locality of other colonised sites, only vestigial evidence of marine wood borers were found on the *London*, thus it is likely that although they were active in the vicinity, a further factor has impeded their survival (Table 5).

4.3 Wood Type

Whilst *Limnoria* and *C.terebans* preferred pine test panels, results indicated Teredinidae were less selective and no relationships were observed between the total number of boreholes or successful boreholes in relation to wood type (Table 5). This is likely due to their life history strategies; Teredinidae are opportunistic with a limited window to locate a suitable substrate in their larval form (Appelqvist et al 2015, Lippert et al 2017), thus they cannot be overly selective and using chemical cues to determine a suitable location near conspecifics with available space is likely prioritised (Toth et al 2015); this behaviour may explain results seen on Poole Cannon Site where a higher number of total boreholes were identified on elm test panels (Table 4). On the other hand, *Limnoria* and *C.terebans* are born into a protective environment and have the ability to migrate in search of substrate material and, move at will when conditions become unfavourable (Mohr 1959, Cragg et al 1999, Poore et al 2002, Thiel 2003, Green Etxabe 2013); this is evident on the *London* where borings were present but no abundance of *Limnoria* was found, thus *Limnoria* likely migrated when sediment coverage occurred. Fouling species showed a preference to hardwoods and were responsible for the highest mean surface area loss on elm test panels across all sites (Fig.7), this is potentially due to the need for a hard substrate with a stable base to adhere to; this would appear to be a sensible choice due to *Limnoria* and *C.terebans’* preference to the pine test panels which lost 46% more surface area compared to the elm test panels. Hence, UCH sites with exposed pine elements such as the pine clad orlop deck found on HMS *Invincible* (Pascoe et al 2017) should be considered high risk.

4.4 Sediment

Sediment type appeared to be a key factor controlling biodegradation and the abundance of marine wood boring and fouling species. Muckelroy (1978), Ward et al (1999) and Wheeler (2002), hypothesised that fine, soft sediments such as silt, compact tightly together creating anoxic conditions, even with minimal sediment coverage; whilst coarse sediments such as gravel cannot, and so dissolved oxygen moves between the sediment particles, enriching deeper layers. Thus, minimal or shallow sediment coverage provides little to no protection on sites with coarse sediments and only articles buried far deeper in these environments have a chance of survival. Dissolved oxygen is a dominant factor in the survival of marine wood boring and fouling species and subsequently, the survival of archaeological material. As a result, the reburial of UCH is considered an effective means of *in situ* protection, with studies indicating a minimum coverage depth of 50 cm is needed to reduce dissolved oxygen enough to impede the survival of wood degrading species (Gregory 1998, Palma 2005, Curci 2006, Manders 2006, Bjordal & Nilsson 2008, Palma & Parham 2009). The *London* had the lowest species abundance and biodegradation of all sites (Fig.7), (Table 6) with only vestigial evidence of *Limnoria* and Teredinidae identified. Hence, it is highly likely the silt sediment covering the test panels reduced the dissolved oxygen levels, which consequently, impeded the survival of the wood boring and fouling species. In comparison with other sites, the relationship between sediment type and its ability to effect dissolved oxygen is commonly observed; the *Mary Rose* (Quinn et al 1997), (prior to excavations) and the *Vasa* (Cederlund & Hocker 2006), buried in soft sediments like the *London* (Evans 2017), have produced incredibly well preserved remains, whilst sites such as *HMS Colossus* (Camidge 2009), *Swash Channel Wreck* (Palma & Parham 2006), and HMS *Invincible* are offered little protection from coarse sediments, and biodegradation is extensive.

5.0 Conclusion

5.1 Future Site Management

Despite limitations, the results provide an insight into the biodegradation occurring on each of the sites which can be applied to future management plans. HMS *Invincible* and the *London* are both on the Heritage at Risk Register due to highly dynamic and unstable site conditions, leading to the loss of historically important. As a result, both sites have undergone several excavations to retrieve at risk artefacts and regular monitoring is undertaken. Whilst UNESCO's (2001) recommendation is that *in situ* preservation should be considered the first option over excavation, it is simply not a viable option for these sites, and despite *in situ* protection, scour, erosion and the loss of material is highly evident (pers comm). Results from this study highlight a stark difference in the rate biodegradation occurring on the sites, and whilst it is fair to argue HMS *Invincible* is the higher priority site, this does not mean the *London* should not be considered high priority. Whilst it is clear HMS *Invincible* is at high risk of biodegradation, the environmental conditions which act upon the site are uncontrollable and expose the site to further biological and physical degradation. Whilst *in situ* protection may slow the rate of degradation, exposure of the ship's structure will continue to occur, losing about 2% of its surface area per month. Hence, the recording and survey work produced as a result of the excavation allowed for the structure and construction method of HMS *Invincible*, which has made her so historically important; to be recorded and understood before it is lost. The *London*, despite a lack of evidence in this study to suggest it is at risk of biological degradation, is at risk due to other elements, namely the dynamic physical conditions acting upon the site; the passing of large ships and dredging activities, alongside strong water movements result in sporadic exposure and the mobilisation and dispersal of sediment and artefacts. Although results from this study indicated that the sediment offers protection from wood boring species, the wood borer damage to the exposed gun carriage raised in 2015 is a stark reminder of what can occur on this site when sediment movement produces long term exposure and allows for wood borer settlement. Hence, funding should be prioritised for both these sites to enable continued monitoring, recovery and conservation for at risk artefacts and *in situ* protection where possible. The Poole Cannon Site is not protected; however it does highlight the need for continued monitoring and *in situ* preservation on stable sites, and illustrates the potential for oxygen to penetrate coarse sediments, allowing for biodegradation. As a result, sites in similar conditions to Poole Cannon Site should be regularly monitored especially as being shallow with coarse sediments, puts them at risk during events such as storms, which can lead to exposure and biodegradation. Additionally, the West Bay site gave promise that wood borers are not active everywhere and, in areas with a lack of wooden material, populations have declined, thus the continued use of *in situ* preservation to limit exposed wooden material is recommended. Nonetheless, it was clear the presence of fouling species ultimately results in a heavy loss of original surface area. Currently, the West Bay wreck is protected due to the presence of a bronze gun, however, regular monitoring is confirming the surface detail on the gun is being lost due to the colonisation of fouling species; and so, aside from recording and survey, recovery or *in situ* protection may be the only way to protect the information (pers comm).

5.2 Further research

The study highlighted key factors for consideration in regard to the rate of biodegradation on wooden UCH caused by marine wood borers; however, in light of the short deployment period, small number of test panels, and small number of sites and environments, further work should be completed to ascertain a more comprehensive dataset where a variety of variables can be tested.

To develop upon the key limitations, a larger selection of wreck sites and environments need to be utilised, with a wider coverage along the south coast of England. Furthermore, the number of test panels needs to be increased, and the deployment time should be extended over 12, 18 and 24 months; not only should this help to encase a wider variety of environments and conditions for comparison, a larger number of test panels should provide a larger data set for stronger statistical analysis. Additionally, a longer study should allow for seasonal comparison and better understanding of wood borer behaviours.

Further research should be completed in regard to some of the factors highlighted throughout the study. Although it was interesting to note that depth did not appear to be a key factor controlling biodegradation, all sites within the study, and those identified as case studies were located within the preferred depth range of wood boring species, and therefore may account for the lack of significant differences observed; hence, a study incorporating a larger variety of depths, including those deeper than 30 m, should provide clarification on the role of depth in species abundance and biodegradation.

Whilst it was evident *Limnoria* and *C.terebans* had a preference to pine test panels, results indicated Teredinidae were less selective when it came to wood type and no significant differences were noticed between the soft and hardwoods. Although this may be due to their life history strategy, laboratory research using a variety of wood types and cuts could identify if a preference is present and would expand upon research completed by Eriksen et al (2016).

Sediment type and coverage proved to be a significant factor for the survival of wooden material, and highlighted sites with compact soft sediment coverage were considered low risk to biodegradation, whilst sites with coarse, shallow, mobile sediments, which leave the site exposed to physical and biological degradation were considered high risk, hence measures for *in situ* protection should be applied immediately to prevent the loss of original material. Nonetheless, further research should aid in emulating a stronger understanding of sediment conditions on sites, and research should focus towards testing a wider range of sites with varying sediments. It may prove worthwhile placing control panels in the water column to provide comparison between those at seabed and those buried at selected depths to better understand the effect and level of protection the sediment is able to offer.

Finally, amendments to the method could be made if sufficient funding could be obtained; the use of X-ray is an inherently easy method of observing the presence and damage caused by Teredinids. However, as a 2D image, X-ray has its limitations, and whilst CAD software programmes can be utilised to create 3D structures from this image with impressive accuracy, the use of CT scanning may provide far more accurate results. Ultimately, the use of X-ray and CAD failed during this study when the level of colonisation became so heavy that individual tunnels could not be separated from a 2D image alone, and as such, CT scans may be more apt at separating individual tunnels and calculating more accurate 3D measurements, even when colonisation is high.

Results produced throughout this study have not only highlighted the need for continued monitoring of all historically important sites, regardless of environmental conditions and stability, but have also determined sediment type and coverage as a significant factor for the survival of wooden material. Thus sites with compact soft sediment coverage should be considered low risk to biodegradation, whilst sites with coarse, shallow, mobile sediments, which leave the site exposed to physical and biological degradation should considered high risk, and measures for *in situ* protection should be applied immediately to prevent the loss of original material, although in many cases, the recovery of at risk artefacts and excavation may be the only option for preservation. Furthermore, in light of some of the limitations to the study, further research focusing on single variables can aid in formulating a more comprehensive dataset which can aid in the protection of our UCH.

6.0 References

Anderson J.W & Reish D.J, 1967. The effects of varied dissolved oxygen concentrations and temperature on the wood boring isopod genus Limnoria. *Marine Biology* 1, 56. DOI:10.1007/BF00346695

Appelqvist C, Al-Hamdani Z.K, Jonsson P.R, Havenhand J.N, 2015. Climate Envelope Modeling and Dispersal Simulations Show Little Risk of Range Extension of the Shipworm, Teredo navalis (L.), in the Baltic Sea. *Plos One 10(3)* e0119217. doi:10.1371/ journal.pone.0119217

Appelqvist C, Havenhand JN, 2016. A phenological shift in the time of recruitment of the shipworm, *Teredo navalis* L., mirrors marine climate change. *Ecology and Evolution* 6: 3862-70. doi: 10.1002/ece3.2126

Bernard F.R, Cai Y.Y & Morton B, 1993. *Catalogue of the living marine bivalve molluscs of China.* Hong Kong University Press: Hong Kong

Björdal C.G & Nilsson T, 2008. Reburial of shipwrecks in marine sediments: a long-term study on wood degradation. *Journal of Archaeological Science* 35 (4) 862-872 doi:10.1016/j.jas.2007.06.005

Borges L. M. S, Valente A. A, Palma P, Nunes L, 2010. Changes in the wood boring community in the Tagus Estuary: A case study. *Marine Biodiversity Records 3.* doi:10.1017/S1755267210000370; Vol. 3; e41; 2010

Borges L.M.S, 2014. Biodegradation of wood exposed in the marine environment: Evaluation of the hazard posed by marine wood-borers in fifteen European sites. *International Biodeterioration & Biodegradation* 96, 97-104. http://dx.doi.org/10.1016/j.ibiod.2014.10.003

Borges L.M.S, Merckelbach L.M, Sampaio I, Cragg S. M, 2014 a. Diversity, environmental requirements, and biogeography of bivalve wood-borers (Teredinidae) in European coastal waters. *Frontiers in Zoology* 11: 13

Borges L.M.S, Merckelbach L.M, Cragg S.M, 2014 b. Biogeography of Wood-Boring Crustaceans (Isopoda: Limnoriidae) Established in European Coastal Waters. *PLoS ONE* 9(10): e109593. https://doi.org/10.1371/journal.pone.0109593

Bowens A, 2009. Chapter 4: Basic principles – Making the most of the clues. *In:*Underwater Archaeology The NAS Guide to principles and practice, pg.30

Camidge K, 2009. *HMS Colossus*, an Experimental Site Stabilization. *Conservation and management of archaeological sites*, Vol. 11 No. 2, 161–88. DOI:10.1179/175355210X12670102063742

Castello, J, 2011. The genus Limnoria (Limnoriidae, isopoda, crustacea) in Europe, including a key to species. *Zootaxa* 2968, 1e25.

Cederlund C. O. & Hocker F, 2006. *Vasa I: The Archaeology of a Swedish Warship of 1628.* Oxford: Oxbow Books. pp.400

Childs D, 2009. *Tudor Sea Power: The Foundation of Greatness. Barnsley*: Seaforth Publishing pg.36.

Coe W. R, 1943. Sexual differentiation in mollusks. 1. Pelecypods. *Quarterly Review of Biology* (U.S.A.) 18:154-164.

Cookson L.J, 1991. Australasian species of Limnoriidae (Crustacea: Isopoda). *Memoirs of the Museum of Victoria,* 52(2):137-262.

Couper, A, 2000. Chapter 6: Supplying the World. *In:* The Conway History of Seafaring in the Twentieth Century. London: Conway Maritime Press, pg.100,102

Cragg S.M, Pitman A.J, Henderson S.M, 1999. Developments in the understanding of the biology of marine wood boring crustaceans and in methods of controlling them. *International Journal of biodeterioration and biodegradation* 43 197-205

Cragg S.M, Jumel M.C, Al-Horani F.A, Hendy I.W, 2009. The life history characteristics of the wood-boring bivalve *Teredo bartschi* are suited to the elevated salinity, oligotrophic circulation in the Gulf of Aqaba, Red Sea. *Journal of Experimental Marine Biology and Ecology* 375, 99–105. doi:10.1016/j.jembe.2009.05.014

Crumlin-Pedersen O, 1984. Aspects of wood technology in medieval shipbuilding. *In*: Crumlin Pedersen, O., Vinner, M. (Eds.), Sailing into the Past: the International Ship Replica Seminar. Viking Ship Museum, Roskilde.

Curci J, 2006. The Reburial of Waterlogged Archaeological Wood in Wet Environments. *Technical Briefs in Historical Archaeology,* 1: 21–25

Doochin H & Smith F. G. W, 1951. Marine boring and fouling in relation to velocity of water currents. *Bull. Mar. Sci. Gulf Caribb.* 1 (3): 196-208.

Eaton R.A & Hale M.D, 1993. *Wood: Decay, pests and protection*. London: Chapman and Hall Ltd, pp546

Elam M, 2009. Pacific Northwest Aquatic Invasive Species Profile Great Naval Shipworm *Teredo navalis. Fish 423*. http://depts.washington.edu/oldenlab/wordpress/wp-content/uploads/2013/03/Teredo-navalis_Elam.pdf (Accessed 14/08/2018)

Eltringham S.K, & Hockley A. R, 1961. Migration and reproduction of the wood boring isopod, Limnoria, in Southampton water. *Limnology and Oceanography,* 6 (4) 467-481

EN275, 1992. *Wood preservatives - Determination of Protective Effectiveness against Marine Borers. British Standard EN 275:1992. CEN*. The European Committee for Standardization, Brussels.

Eriksen A.M, Gregory D.J, Boltfeldt K, 2014. The survival of Teredo navalis L in timber wrapped in TERRAM4000 and plastic membrane. *International Biodeterioration and biodegradation,* 86, 96-101 http://dx.doi.org/10.1016/j.ibiod.2013.06.021

Eriksen A.M, Gregory D & Shashoua Y, 2015. Selective attack of waterlogged archaeological wood by the shipworm, *Teredo navalis* and its implications for in-situ preservation. Journal of Archaeological Science 55, 9-15. http://dx.doi.org/10.1016/j.jas.2014.12.011

Eriksen A.M, Gregory D.J, Villa C, Lynnerup N, Botfeldt K.B, Rasmussen A.R, 2016. The effects of wood anisotropy on the mode of attack by the woodborer *Teredo navalis* and the implications for underwater cultural heritage. *International Biodeterioration and Biodegradation* 107, 117-122 http://dx.doi.org/10.1016/j.ibiod.2015.11.018

Evans S, 2017. The London: Updated Statement and Conservation Management Plan, 2017. *Research Report Series* no. 86-2017. A report prepared for Historic England by Cotswold Archaeology. Available from: http://research.historicengland.org.uk/redirect.aspx?id=7200%7CThe%20London:%20Updated%20Conservation%20Statement%20and%20Management%20Plan%202017 (Accessed 15/08/2018)

Florian M.L.E, Seccombe-Hett D.E, McCawley J.C, 1977. The Physical, Chemical and Morphological Condition of Marine Archaeological Wood Should Dictate the Conservation Process. *The First Southern Hemisphere Conference on Maritime Archaeology*, Perth, Australia, pp. 128-144.

Fofonoff P.W, Ruiz G.M, Steves B, Simkanin C, Carlton J.T, 2018 a. *Lyrodus pedicellatus*. National Exotic Marine and Estuarine Species Information System. Available from: http://invasions.si.edu/nemesis/ (Accessed 15/08/2018)

Fofonoff P.W, Ruiz G.M, Steves B, Simkanin C, Carlton J.T, 2018 b. *Limnoria quadripuntata*. National Exotic Marine and Estuarine Species Information System. Available from: http://invasions.si.edu/nemesis/ (Accessed 15/08/2018)

Green Etxabe A, 2013. *The wood boring amphipod Chelura terebans.* Portsmouth: Portsmouth University Institute of Marine Sciences. PhD Thesis submitted to Portsmouth University. Available from: http://eprints.port.ac.uk/13832/3/AGreenEtxabe_Thesis.pdf (Accessed 14/08/2018)

Gregory D, 1998. Re-burial of timbers in the marine environment as a means of their long-term storage: experimental studies in Lynaes Sands, Denmark. *International Journal of Nautical Archaeology* 27 (4) 343-358. https://doi.org/10.1111/j.1095-9270.1998.tb00814.x

Gregory D, Jensen P, Straekvern K, 2012. Conservation and in situ preservation of wooden shipwrecks from marine environments. *Journal of cultural heritage* 13 (3) 139-14 doi:10.1016/j.culher.2012.03.005

Historic England, 2018. *Protected wreck sites*. Portsmouth: Historic England. https://historicengland.org.uk/advice/planning/consents/protected-wreck-sites/ (Accessed 15/08/2018)

ICOMOS, 1996. *Charter on the protection and management of underwater cultural heritage (1996).* Sofia: ICOMOS. Available from: http://www.icomos.org/charters/underwater_e.pdf (Accessed 13/08/2018)

Jones L.T, 1963. The geographical and vertical distribution of British Limnoria (Crustacea, Isopoda). *Journal of the Marine Biological Association of the United Kingdom*, 43:589-603.doi:10.1017/S002531540002554

Knight K, 2018. A preliminary study on the growth rate of *Lyrodus pedicellatus* (Bivalvia: Teredinidae) within the first 5 months after settlement. *International Biodeterioration and Biodegradation* 132, 185-191. https://doi.org/10.1016/j.ibiod.2018.04.001

Lane C, E, 1959. Some aspects of the general biology of Teredo. *In:* Dixy Lee Ray. *Marine Boring and Fouling Organisms*. Seattle: University of Washington Press; pg. 139

Lippert H, Weigelt R, Glaser K, Krauss R, Bastrop R, Karsten U, 2017. *Teredo navalis* in the Baltic Sea: Larval Dynamics of an Invasive Wood-Boring Bivalve at the Edge of Its Distribution. *Front. Mar. Sci*. 4:331. doi:10.3389/fmars.2017.00331

Litwin J, 1998. Medieval Baltic Ships - Traditions and constructional aspects. *In*: L'innovation technique au Moyen Âge. Actes du VIe Congrès international d'Archéologie Médiévale (1-5 Octobre 1996, Dijon - Mont Beuvray - Chenôve - Le Creusot - Montbard) Caen : Société d'Archéologie Médiévale, 1998. pp. 88-97. (*Actes des congrès de la Société d'archéologie médiévale*, 6)

Macintosh H, deNys R, Whalan S, 2014. Contrasting life histories in shipworms: growth, reproductive development and fecundity. *J Exp Mar Biol Ecol* 459: 80-86. http://dx.doi.org/10.1016/j.jembe.2014.05.015

McGrail S, 2001. Chapter 5.8 Medieval vessels (eleventh – fourteenth centuries). *In:* Boats of the World: from the Stone Age to medieval times. Oxford: Oxford University Press, pg. 224.

Manders M.R, 2006. The *in situ* protection of a Dutch Colonial vessel in Sri Lankan waters. *In:* Grenier R, Nutley D & Cochran I (eds) *Underwater Cultural Heritage at Risk: Managing Natural and Human Impacts*. Paris: ICOMOS, pg.58.

Manders M, Gregory D & Richards V, 2009. The in situ preservation of archaeological sites underwater: an evaluation of some techniques, in Heritage Microbiology and science. In: *Heritage, Microbiology and Science.* Ed May, E, Jones, M and Mitchell, J. pg.180

Manders M, 2011. *Guidelines for the Protection of Submerged Wooden Cultural Heritage.* Available from: www.machuproject.eu/documenten/wreck_protect_guidelines_protection_wood.pdf (Accessed 13/08/2018)

Manders M & Gregory D (eds), 2015 a. *Guidelines to the process of underwater archaeological research, SASMAP Guideline Manual 1.* Amersfoort, Netherlands: SASMAP. Available from: http://sasmap.eu/fileadmin/user_upload/temasites/sas_map/pdf/SASMAP_guideline_01_LR.pdf (Accessed 13/08/2018)

Manders M & Gregory D (eds), 2015 b. *Best practices for locating, surveying, assessing, monitoring and preserving underwater archaeological sites, SASMAP Guideline Manual 2.* Amersfoort, Netherlands: SASMAP. Available from: http://sasmap.eu/fileadmin/user_upload/temasites/sas_map/pdf/SASMAP_guideline_02_LR.pdf (Accessed 13/08/2018)

Manders M, 2017. Threats to underwater cultural heritage. *In:* Preserving a layered history of the Western Wadden Sea, Managing an underwater cultural heritage resource. Cultural Heritage Agency of the Netherlands. pg. 68, 72, 83

Menzies R.J, 1957. The marine borer family Limnoriidae (Crustacea, Isopoda). Part I: northern and central America: systematics distribution, and ecology. *Bull. Mar. Sci. Gulf Caribb*. 7, 100e200.

Menzies R. J, Mohr J, Wakeman C.M, 1963. The seasonal settlement of wood-borers in Los Angeles - Long Beach Harbours. *Wasmann J. Biol*. 21: 97-120.

Merrett Jones, M, 2000. *The effect of sewage enrichment upon the integrity of the fabric of marine sites of archaeological importance.* PhD Thesis submitted to Surrey University, Guildford. Available from: http://epubs.surrey.ac.uk/770239/1/Merrett-Jones_2000.pdf

Mohr J, 1959. On the protozoan associations of Limnoria. *In*: Dixy Lee Ray. Marine Boring and Fouling Organisms. Seattle: University of Washington Press, pp.84-95

MoSS, 2003. *Monitoring, Safeguarding and Visualising North European Shipwreck sites: Common European Underwater Cultural heritage Final Report.* Financed through the EU Culture Resource. Available from: http://moss.nba.fi/download/final_report.pdf (Accessed 13/08/2018)

Muckelroy K, 1978. Part Two: Towards a theory of maritime archaeology. In: New studies in Archaeology - Maritime Archaeology. Cambridge: Cambridge University Press pg. 162-164, 176

Nair N.B, Saraswathy M, 1971. The biology of wood boring teredinid molluscs. *Adv Mar Biol*, 9, 355–509.

Paalvast P & Van der Velde G, 2011. Distribution settlement and growth of first year individuals of the shipworm *Teredo navalis* L. (Bivalvia: Teredinidae) in the port of Rotterdam, the Netherlands. *International Biodeterioration and Biodegradation* 65, 379-388 doi:10.1016/j.ibiod.2010.11.016

Palanti S, Feci E, Anichini M, 2015. Comparison between four tropical wood species for their resistance to marine borers (Teredo spp and Limnoria spp) in the Strait of Messina. *International Journal of Biodeterioration and Biodegradation* 104, 472-476 http://dx.doi.org/10.1016/j.ibiod.2015.07.013

Palma P, 2005. Monitoring of Shipwreck Sites, *International Journal of Nautical Archaeology*, 34 (2), 323–331. doi: 10.1111/j.1095-9270.2005.00064.x

Palma P & Parham D, 2006. *Swash Channel Wreck: 2006 Season Report*. An unpublished report produced for Poole Harbour Commissioners. Available from: https://www.phc.co.uk/downloads/environment/env_harbourmon_appen11_0807.pdf (Accessed 13/08/ 2018)

Palma P & Parham D, 2009. *Swash Channel Wreck: Project Report for Environmental Scoping Study for In Situ Stabilization of the Site*. Unpublished report for English Heritage.

Palma P, 2010. *West Bay Designated Wreck, Monitoring Project.* A report produced for Historic England by Bournemouth University.

Pascoe D, 2013. *A new era of investigation on the Royal Navy's first HMS Invincible*. A report prepared for the British Sub Aqua Jubilee Trust

Pascoe D & Cowan C, 2017. *HMS Invincible* (1758) Horse Tail, Eastern Solent, off Portsmouth. Conservation Statement and Management Plan. *Research Report Series no. 27-2017.* Portsmouth: Historic England. Available from: http://research.historicengland.org.uk/redirect.aspx?id=6746%7C%20HMS%20Invincible%20(1758)%20Conservation%20Statement%20and%20Management%20Plan (Accessed 16/08/2016)

Pascoe D, Jones B & Cox G, 2017. The Use of Multi-Image Photogrammetry to Record At-Risk Archaeological Material from the Wreck of *Invincible*. *Research Report Series no. 37-2017*. Portsmouth: Historic England. Available from: http://research.historicengland.org.uk/redirect.aspx?id=6764%7CThe%20Use%20of%20Multi-Image%20Photogrammetry%20to%20Record%20at%20Risk%20Archaeological%20Material%20from%20the%20Wreck%20of%20Invincible (Accessed 16/08/2016)

Pater C, 2007. *MACHU - Managing Cultural Heritage Underwater Report Number 1.* Portsmouth: English Heritage. Available from: https://www.machuproject.eu/documenten/MACHU_report_1.pdf [Accessed 14/08/2018]

Poore G.C.B, Cookson L. J, Lew Ton H.M, 2002. Limnoriidae. *In*: Zoological Catalogue of Australia, *Volume 19 of Crustacea : Malacostraca: Syncarida, Peracarida : Isopoda, Tanaidacea, Mictacea, Thermosbaenacea, Spelaeogriphacea*. Poore G.C.B. Clayton, Australia: Csiro Publishing. pg 201

Quayle D.B, 1992. Marine wood borers in British Columbia. Can. Spec. Publ. *Fish. Aquai. Sci.*115 pg.55

Quinn, R, Bull J. M, Dix J. K, Adams J. R, 1997. The Mary Rose site-geophysical evidence for palaeo-scour marks. *International Journal of Nautical Archaeology* 26, 3–16.

Shalaeva E, 2012. *Limnoria lignorum*. CABI Invasive Species Compendium. Available from: https://www.cabi.org/isc/datasheet/109146 (Accessed 14/08/2018)

Sivrikaya H, Cragg S.M, Borges L.M.S, 2009. Variation in resistance to marine borers in commercial timbers from Turkey, as assessed by marine trial and laboratory screening. *Turk J Agric For*, 33, 576. doi:10.3906/tar-0902-28

Smith J. R, 2009. Shipbuilding and the English International Timber Trade, 1300-1700: a framework for study using Niche Construction Theory. *Nebraska Anthropologist* 49. Available from: http://digitalcommons.unl.edu/nebanthro/49 [Accessed 08/11/2018]

Stewart D.J, 1999. Formation processes affecting submerged archaeological sites: An Overview. *Geoarchaeology: An International journal* 14 (6) 565-587

Thiel M, 2003. Reproductive biology of *Limnoria chilensis*: another boring peracarid species with extended parental care. *Journal of Natural History*. 37 (14) 1713-1726. doi:10.1080/00222930210125416

Toth G.B, Larsson A.I, Jonsson P.R, Appelqvist C, 2015. Natural Populations of Shipworm Larvae Are Attracted to Wood by Waterborne Chemical Cues. *PLoS ONE* 10(5): e0124950. https://doi.org/10.1371/journal.pone.0124950

Turner R.D, 1966. *A survey and illustrated catalogue of the Teredinidae*. The Museum of Comparative Zoology, Harvard University, pp.265

Turner R.D, 1971. Methods of identification of marine borers and fungi. *In:* Marine borers, fungi and fouling organisms of wood. Jones SK, Eltringham GEB (eds), Organisation for Economic Co-operation and Development, France, pp 18–63

UNESCO, 2001. *Underwater cultural heritage. Text of the 2001 Convention.* Paris: UNESCO. Available from: www.unesco.org.new/en/culture/themes/u-c-h/2001-convention/offical-text/ (Accessed 13/08/2018)

Valetta Treaty, 1992. *European Convention on the Protection of the Archaeological heritage (revised).* [Online] Valetta: Council of Europe. Available from: https://rm.coe.int/CoERMPublicCommonSearchServices/DisplayDCTMContent?documentId=090000168007bd25 (Accessed 13/08/2018)

Vego M, 2016. Chapter 3: Obtaining and Maintaining Sea Control . *In:* Maritime Strategy and Sea Control: Theory and Practice. Routledge: Abingdon. pg. 56

Voight J.R, 2015. Xylotrophic bivalves: aspects of their biology and the impacts of humans. *Journal of Molluscan Studies* 81: 175-86. doi:10.1093/mollus/eyv008

Ward I.A.K, Larcombe P, Veth P, 1999. A new process-based model for wreck site formation *J. Archaeol. Sci.,* 26 pp. 561-570

Weiss C. M, 1948. An Observation on the Inhibition of Marine Wood Destroyers by Heavy Fouling Accumulation. *Ecology* 29 (1) 120. https://doi.org/10.2307/1930351

Wheeler A.J, 2002. Environmental Controls on Shipwreck Preservation: The Irish Context. *Journal of Archaeological Science* 29, 1149–1159 doi:10.1006/jasc.2001.0762

Wurzinger Mayer A, Shipway R, Kristof A, Scwaha T, Cragg S, Wanninger A, 2014. Developmental dynamics of myogenesis in the shipworm Lyrodus pedicellatus (Mollosca: Bivalvia). *Frontiers in Zoology* 11:90. doi:10.1186/s12983-014-0090-9

7.0 Conflicts of Interest

The authors declare that they have no conflict of interest.

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