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Biodegradation of wood exposed in the marine environment: evaluation of the hazard posed by marine wood-borers in fifteen European sites

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Abstract

The activity of marine wood-borers causes great destruction in maritime wooden structures. Therefore, the aim of this study was to evaluate the hazard posed by marine wood-borers in fifteen European sites, to assist authorities and researchers concerned with the protection of wood in the sea. In northern Europe, *Teredo navalis* is the species that poses the highest borer hazard while in the Atlantic coast of southern Europe *Lyrodus pedicellatus* is the most destructive species, with the exception of two sites in Portugal. In these sites, *Limnoria tripunctata* was more destructive than *L. pedicellatus*. In the Mediterranean both *T. navalis* and *L. pedicellatus* pose a very high borer hazard to wooden structures.
Salinity and temperature emerged as the environmental conditions that best explain the occurrence and abundance of wood boring species in the sites surveyed. Three of the species highlighted in this study are warm water species. Therefore their activity might increase in the future, due to global warming. Considering that wood is still a very valuable material for construction, its use for maritime construction should be favoured. Thus research to improve the durability of wooden materials in the marine environment is of paramount importance.

Keywords biodegradation of wood; marine wood-borers; teredinids; shipworm; limnoriids; gribble borer hazard; European coastal waters.

1. Introduction

In human history, wood has been the material used for maritime construction, possibly due to its wide availability and relative ease of fabrication and repair (Eaton and Hale, 1993; Cragg, 1996). For centuries, it has been the sole resource used in the construction of rafts, boats, ships and harbour structures (Cragg *et al*., 2001). In the past, the economy of seafaring nations depended upon their ability to maintain a sea-worthy fleet (Graham, 1973). Nowadays, wooden ships no longer play a major role in maritime commerce, but wood is still, a very important component of marine infrastructure in many countries (Love *et al*., 2000). However, wooden structures in the marine environment are vulnerable to attack by a group of xylotrophic organisms, collectively known as marine wood-borers, which are voracious consumers of wood (Betcher *et al*., 2012). This group includes Bivalvia (Teredinidae and Pholadidae), Isopoda (Limnoriidae and Sphaeromatidae), and Amphipoda (Cheluridae). In Europe most wood-boring bivalves belong to the Teredinidae, but species of the Pholadidae, such as Xylophaga dorsalis (Turton, 1819), also has been reported occurring in Europe (Santhakumaran and Sneli, 1978; Eaton *et al.*, 1989). Wood-boring Crustacea occurring in Europe belong to the Limnoriidae and Cheluridae.
The fight against wood-boring ravage has been going on since early historic times (Turner and Johnson, 1971). From the literature and wrecks, it is known that the ancient Egyptians and

Chinese, for instance, used protective coatings, such as resin, pitch or paint, and hull sheathing in their ships, in addition to regular beaching and drying (Steinmayer and Turfa, 1997). These methods probably provided a certain degree of protection to ships and boats. However, the advent of long exploration voyages that started in the 15th century, using large wooden ships, brought about new challenges. The destructive activity of wood borers was very problematic for sailors, but it was probably not felt as a vital problem for nations. This changed in 1730 in the Netherlands, when the country was under the threat of being flooded due to the huge destruction caused by wood borers in the wooden-faced dykes. The prospect of sudden calamity aroused a general interest in marine wood borers (Sellius,1733; Vrolik,1858). Since then, accounts of serious economic problems caused by the activity of wood borers have been documented in Europe (e.g. Schütz, 1961; Hoppe, 2002). Several methods have been developed with the aim of protecting wood exposed in the sea against marine borers. However, the control of marine wood borers remains an unresolved problem. In addition, the EU directive (European Commission, 2003) is now limiting the use of established and proven preservatives, such as creosote and copper-chrome-arsenic (CCA), in wood destined to be used in marine construction. Therefore, other approaches need to be explored to ensure an adequate service life for timber exposed in the sea. One approach has been to investigate the natural durability against marine wood borers of lesser utilised timbers species using laboratory tests (Rosenbusch *et al*., 2006; Borges *et al.*, 2008) or field trials (Edmondson, 1955; Southwell and Bultman, 1971; Jones *et al*., 1972; Haderlie, 1983; Bultman *et al*., 1988; Eaton *et al*., 1989; Williams *et al*., 2004). Another approach, which has been developed in recent years, is the chemical modification of wood for use in the marine environment (Borges *et al*., 2005; Westin and Rapp, 2005; Lopes *et al.*, 2014).

The destruction caused by wood borers to wooden maritime structures has led to the choice of other materials, such as concrete and steel, for use in the marine environment. These materials are dominant in marine developments in countries such as the UK (Reynolds, 2004) and Portugal (Borges, pers. obsv.). Nevertheless, the properties of wood, such as resilience, favourable strength-to-weight ratio, relatively low energy costs of production and renewability, make it an attractive material to use for construction (Borges *et al*., 2003). Wood also suffers much less from the effect of the salt in the seawater than for instance steel or concrete (Williams *et al*., 2004), and a growing tree absorbs more carbon from the atmosphere than it emits and its processing also requires less energy than the production of concrete or steel (Burnett, 2006). In addition, the production of cement and steel alone accounts for over 10% of global annual greenhouse gas emissions (Burnett, 2006).Therefore, in line with the commitment of the European Union to reduce the emission of greenhouse gases, wooden materials, when the wood is obtained from sustainable sources, are more environmentally friendly and, therefore, should be favoured in marine construction. To this end, having knowledge on wood boring hazard in the area(s) is desirable to enable the choice of the most adequate wooden specie or for future development of tailor-made treatments. However information on borer hazard in European waters is very scarce, although some sites have been used to test the durability of a number of potentially durable wooden species and treated wood. Thus the wood borer hazard to untreated non-resistant wood, Scots pine, used as a comparator, is known (e.g. Jones *et al.*, 1972; Eaton *et al.*, 1989). However, according to EN 275 (1992) the sites chosen for these tests should have high borer hazard. Thus, the borer hazard from these sites is probably not representative of that in other sites in European coastal waters.

Therefore, the aims of the present study were to evaluate the borer hazard posed by teredinids and limnoriids to non-durable timber (*Pinus sylvestris* L.) using a standard methodology EN 275 (1992) to give information on the maximum severity of attack in the sites surveyed; to make it possible to compare with results from other studies (e.g. Eaton *et al*., 1989); to correlate the abundance of wood boring species in these sites with environmental factors. This information may assist researchers and authorities concerned with service life and protection of wood in the marine environment.

2- Materials and Methods

2.1- Experimental set-up and laboratory assessment of test panels

To evaluate the severity of attack caused by wood borers in 15 sites in European waters (Fig.1), collaborators (see acknowledgements) exposed six panels of *Pinus sylvestris* L. (Scots pine) at each site. The number of replicates follows the standard EN 275 (1992), which advises the use of at least five replicates. The main aim of EN 275 is to evaluate the relative effectiveness of a wood preservative applied by vacuum/pressure impregnation in the marine environment. In the present study the method was modified to suit the aims of the study (see above) and therefore only untreated Scots pine was used. The wood was uniform, straight-grained and free of knots, cracks, stains or other defects (EN 275, 1992). For detailed methodology, please refer to Borges *et al*., (2014). Data on monthly surface temperature and salinity at each site were provided by the collaborators for the majority of test sites (Table 1).

After one year´s exposure, the panels were removed and the severity of attack by marine borers was assessed. The fouling community was carefully scraped off. The surface of the panels was then inspected for signs of limnoriid attack. To identify the limnoriid species present, specimens were extracted from the wood and identified using the keys in Menzies (1957), Kühne (1971), Cookson (1990) and Castelló (2011). The severity of attack caused by teredinids was visually assessed using X-rays of the panels, and by splitting the panels to reveal the extent of interior damage and extract the specimens or, in certain cases, just the shells and the pallets. Teredinids were identified on the basis of the morphology of the pallets, using the keys in Turner (1971), the illustrations in Turner (1966) and later using molecular markers *(*Borges *et al.*, 2012).

To quantify the severity of wood boring damage in the test panels caused by limnoriids and teredinids, the ranking system described in EN 275 (1992) was used. This system varies from 0 (no attack) to 4 (maximum attack, complete destruction of the wood). The abundance of teredinids and limnoriids was determined by counting the specimens found. In the case of teredinids the number of specimens was estimated also by counting the number of shells and pallets, when only these were found in the wood. In addition, the number of tunnels in X-rays of panels was counted whenever possible, but in some cases, due to heavy attack, it was not possible to differentiate individual tunnels.

2.2- Statistical analysis

Differences in species composition and abundance were compared using multivariate analysis in PRIMER V6 (Clarke and Gorley, 2006). The `analysis of similarities´ and species contribution ANOSIM was carried out to test the null hypothesis that there are no differences in the species composition between the sites tested. The data was square-root-transformed, prior to produce the Bray-Curtis similarity matrix (Clarke 1993). The following hierarchical design was used (orthogonal, fixed, 15 levels). The similarity percentage (SIMPER) routine was then used to identify the relative species contribution to the differences observed between test sites (pairwise comparison) (Clarke and Gorley, 2006).

The Bio-Env analysis on BEST routine, in the PRIMER package V6, was used to test how variability and abundance of species could be explained by environmental differences (Clarke and Gorley, 2006). Several environmental factors have been identified as having influence on marine wood-borers. Thus, the factors with the highest influence on the survival and activity of marine wood-borers were tested, including temperature, salinity, dissolved oxygen and pH (Menzies, 1957; Turner, 1966; Nair and Saraswathy, 1971) (Table 1). The data on temperature salinity was obtained from the hybrid dataset compiled by Borges *et al.* (2014). Data on dissolved oxygen and pH was extracted from Tyberghein *et al.* (2012). The analysis was based on the high rank correlation between the similarity matrix generated using the Bray-Curtis similarity coefficient on square-root-transformed abundance data, and the similarity matrix constructed using the Euclidean distance on normalized temperature, salinity, dissolved oxygen and pH data. Different combinations of variables were tested, and the group of variables that gave the highest correlation was taken as the variables that `best´ explained the biotic structure observed in test panels. The significance of the relationship was based on random permutations of the data (99).

3. Results

3.1 Severity of wood boring attack at test site

In most test sites surveyed teredinids caused higher severity of attack than limnoriids (Figs. 2 and 3). The high borer hazard in most northern European sites was caused mainly by *Teredo navalis* Linnaeus, 1758. Indeed, *T. navalis* caused complete destruction of test panels exposed near Kristineberg Marine Research Station, Sweden, Roskilde, Denmark (Fig. 2) and also in Bartin, northern Turkey, where it was the only species present (in all test sites the six replicate wooden panels scored 4). In other sites such as Kiel, Germany, Haren (Eemshaven) and Yerseke, The Netherlands, test panels were not completely destroyed but the destruction was still considered severe (high borer hazard) (Fig. 3). In these sites however the severity of attack varied among the replicate wooden panels. In Kiel, for example, 2 panels scored 1, two panels scored 2, and the last two scored 3 and 4. In Trondheim, Norway, the borer hazard was due mainly to *Psiloteredo megotara* (Hanley, 1848). Panels exposed in Trondheim, Norway showed a relatively high mean severity of attack by *Psiloteredo megotara* (2.8). Three out of the six test panels exposed in the area showed severe attack, two panels scored 4 and one 3. From the last three panels, two scored 2 and one scored 1. *Limnoria lignorum* also attacked the panels exposed in Trondheim, but the severity was lower than that caused by teredinids (3 panels socred 2 and 3 panels scored 1). The attack on wooden panels in Reykjavik, Iceland, was due only to *Limnoria lignorum* (Rathke, 1799) (Fig. 4). However, the severity of attack in the panels was low (all panels scored 1) (Fig 3). Panels exposed in Dunstaffnage Bay, Scotland, showed signs of limnoriid attack (vestigial), although no limnoriids were found (Fig.3), whereas panels exposed in the Gulf of Riga, Latvia, did not show signs of wood boring attack. Panels exposed in Portsmouth, England were also severely deteriorated (3.8) by the Atlantic form of *Lyrodus pedicellatus* (Quatrefages, 1849), which was the only teredinid species present in the first year of exposure (four panels scoring 4 and two scoring 3 and 3.5). *Limnoria quadripunctata* Holthuis, 1949 was also present but its activity was less destructive (five panels scoring 2.5 and one 3) than that of teredinids. In subsequent years, however, *Teredo navalis* was also present, but *L. pedicellatus* was more abundant and destructive than either *T. navalis* or *L. quadripunctata* (Borges, 2007). In the two sites tested in Portugal, Olhão and Terceira, Azores, the hazard posed by *Limnoria tripunctata* Menzies, 1951 was higher than that by *Lyrodus pedicellatus* (Fig. 3). There was very little variation in the severity of attack by *L. tripunctata* in the test panels in Olhão and in Terceira. The severity of attack by teredinids showed also little variation in Olhão, but in Terceira there was variation from panel to panel (scores varied between 2 and 3). In the two sites tested in the Mediterranean, six wood boring species occurred (see fig. 4), but the species that posed the highest hazard to the test panels was the Mediterranean form of *L. pedicellatus*. Species such as, *Nototeredo norvagica* (Spengler, 1792), *Teredo bartschi* Clapp, 1923, and *Bankia carinata* (Gray, 1827) occurred in low numbers and their severity of attack was negligible. *Limnoria tripunctata* attacked all test panels exposed in Mersin, but only in one panel the destruction was severe (3) in the other panels severity of attack was 2 or less. However, the severity of attack of limnoriids is usually less destructive as it occurs initially in the wood surface. Therefore the ratings of attack of limnoriids and teredinids are not, generally, equivalent. No sign of attack by limnoriids was observed in test panels exposed in Rovinj, Croatia.

3.2 Statistical analysis

There were significant differences in the species composition and their abundance between test sites (ANOSIM: *R*=0.87, *P*= 0.0001), therefore the null hypothesis was rejected. SIMPER analysis indicates that these differences were the result of a greater abundance of *Teredo navalis* in northern European sites such as near Kristineberg Biological Station, Sweden, Roskilde, Denmark, and in Bartin, northern Turkey; *Lyrodus pedicellatus* in Rovinj, Croatia and Mersin, southern Turkey; and *Limnoria tripunctata* in Terceira (Azores) and Olhão, Portugal.
Of the four environmental variables tested, the BEST procedure selected salinity and temperature as the variable combination that showed the highest correlation with the biotic structure present in the test panels (BIO-ENV: Rho=0.523, *P*=0.001, Table 2).

4. Discussion

4.1- Borer hazard in test sites

The results of the present study show significant differences in wood-boring species composition among the sites surveyed (ANOSIM, R=0.87) (Fig. 5). In northern European sites, such as Krisitineberg, Roskilde, Kiel, Haren (Eemshaven) and Yerseke (Fig. 3),*Teredo navalis* was the most abundant species, in some case the sole species present, causing the complete destruction of the panels in the period of one year in the first two sites. It caused also severe attack in the majority of the sites mentioned above. In these sites *Teredo navalis* had little or no competition with other wood boring species during the period of exposure of the panels, which may explain in part the high activity of this species in areas surveyed in the Baltic and North Sea. In addition, of all marine wood borers occurring in Europe *T. navalis* is the species with the widest tolerance for a range of temperature and salinity (Borges *et al*., 2014). In Trondheim, however, *Psiloteredo megotara* was the most destructive species causing severe attack to the test panels (Fig. 3). Although *P. megotara* specimens were less abundant than *T. navalis* specimens in other sites, their large dimensions and continuous growth, even at temperatures as low as 5 °C (Norman,1977), makes them very destructive organisms.
The comparison of the severity of attack in test sites in the present study with previous studies, such as the studies carried out by Santhakumaran and Sneli (1978) and Eaton *et al*. (1989) shows year on year variability in the same site. Santhakumaran and Sneli (1978) observed changes in the composition and abundance of wood boring species in Trondheim fjord. They reported that *Xylophaga dorsalis*, were the most destructive wood-boring organisms attacking all wood species being tested, although *Psiloteredo megotara* was also present and also responsible for large destruction of test panels. However, Nair (1959) reported *Nototeredo norvagica* widely distributed along western Norway, and Dons (1946) also reported its presence in Trondheim fjord. In the present study, however, X. dorsalis did not recruit to the test panels and only one specimen of *N. norvagica* was found. In spite of this natural variation, *Teredo navalis* was never reported to occur in Trondheim, according to the many studies in the area. In the international study by Eaton *et al* (1989) two European sites were used in the trials to test the efficacy of CCA and CCB (copper-chrome-boron) wood preservatives. One of them, Kristineberg was also surveyed in the present study, but both the severity of attack in untreated panels of *Pinus sylvestris* and the wood-borers present were different. In the present study only *Teredo navalis* was present and the panels were completely destroyed after one year´s exposure. In the study by Eaton *et al* (1989) three wood boring species were present, *Psiloteredo megotara*, *Teredo navalis* and *Xylophaga dorsalis*, but the borer hazard was lower than in the present study as untreated panels of *Pinus sylvestris* were destroyed only after 36 months. These comparisons clearly show the year on year variation in the wood-boring community and borer hazard in the same area.
In southern Europe *Lyrodus pedicellatus* is the teredinid species that poses the greatest borer hazard to wooden maritime structures. In some areas along the Atlantic coast of Europe, including southern England, *T. navalis* and *L. pedicellatus* occur in sympatry, which may lead to competition between the two species (Borges *et al*., 2014). The dominance of *L. pedicellatus* is

probably related to its life history strategy. The larvae of *L. pedicellatus* settle in the wood in just 36 hours or less (Lebour, 1946) after being released. Their shorter permanence of in the plankton, compared to that of *T. navalis*, means that they are less exposed to adverse environmental conditions and predators, during the phase which is considered the weak link in the life cycle of teredinids (Turner, 1966). In addtion, it is probable that many of the larvae of *L. pedicellatus* settle in the same piece of wood as the parents, making this a strong competitor species, which provokes great destruction to the wood. In the Mediterranean Sea, *L. pedicellatus* (Mediterranean form) was the most destructive species. However, in other studies, *Teredo navalis* seemed to dominate and was responsible for the high borer hazard observed in test panels (e.g. Sivrikaya *et al*., 2009). Similarly to what occurs in the Atlantic coast, there is probably competition between the Mediterranean form of *L. pedicellatus* and *T. navalis* and, therefore, there is a natural variability in the hazard posed by these species to wooden structures in the area.

The hazard posed by *Limnoria lignorum* in northern European sites is comparatively smaller than that by teredinids (Fig. 3). The severity of attack caused *L. lignorum* to test panels exposed in Reykjavik was low (Fig 3), however this might not be always the case. Saemundsson, (1937) observed that the hazard posed *L. lignorum* in Iceland varied with site and environmental conditions. He observed that in certain areas around Iceland the destruction of wooden structures was severe. In Yerseke the activity of *L. lignorum* in test panels was also small compared to that of *T. navalis*. However in the past limnoriids were observed posing a high hazard to wooden structures in The Netherland (Hoek, 1893 in Clapp & Kenk, 1963). In the present study, *Limnoria quadripunctata* was found only in Portsmouth, England. The destruction caused by this species to the wooden panels was severe (Fig. 3). Furthermore, in several surveys of wooden structures around Portsmouth and other areas in southern England (Borges *et al*. in press) this species was very abundant causing great destruction, in sea defences in Southsea, Portsmouth, Swanage pier (Borges, 2007) and in in Yarmouth pier, Isle of Wight. The costs of repair of the later were ca £400,000 (Cragg, pers. com.). Later surveys revealed that this species is more widespread in southern Europe then previously reported (Borges *et al*., in press) but the severity of its attack in these areas was not yet evaluated. In southern Europe, *Limnoria tripunctata* is also quite widespread. In the present study the test panels exposed in Olhão and Terceira (Azores), Portugal showed higher severity of attack caused by limnoriids than that by *Lyrodus pedicellatus*, the most abundant teredinid species present in both sites. These results seem to show that in spite of its life history strategy traits such as low fecundity and direct development (Cragg *et al.*, 1999), which may limit dispersion, *L. tripunctata* is a good competitor and poses a serious risk for wooden structures exposed in the sea. Recent work has shown that this species seems to be widespread in mainland Portugal and in the Azores (Lopes, 2013; Borges and Costa, in press; Borges *et al*., in press) in areas where it was not previously reported upon. In the Mediterranean, *L. tripunctata* occurred only in Mersin, Turkey, causing severe damage in one out of the six test panels exposed in the area. However in the remaining five panels, the Mediterranean form of *L. pedicellatus* was more destructive than *L. tripunctata*. However this species occurs probably in other areas such as the Venice lagoon, where wooden structures show the characteristic pencil-point shape and hour-glass shape characteristic of limnoriid attack (Borges, pers. obs.).

4.2- Factors affecting the hazard posed by marine wood-borers in the sites surveyed

The higher hazard posed by teredinids to wooden structures compared to that of limnoriids in the majority of the sites surveyed, is probably related to the tolerance of teredinid species, such as *T. navalis* and *L. pedicellatus*, to a wider range of salinity and temperature than limnoriid species (Borges *et al*., 2014; Borges *et al*., in press). Indeed the results of the BIO-ENV (Table 2) showed that temperature and salinity were the two variables that \`best´ explained the patterns of diversity and abundance of marine wood borers in the test sites surveyed. These results corroborate the findings of several studies on the influence of temperature and salinity on the survival and activity of teredinid and limnoriid species (Roch, 1932; Beckman and Menzies, 1960; Eltringham, 1961; Kristensen, 1969; Eckelbarger and Reish, 1972; Borges *et al.* 2014; Borges *et al.* in press).

The life history strategy of teredinids and limnoriids is also a very important factor explaining the differences in the hazard posed by the two groups in the sites surveyed. Teredinids have a larval phase while limnoriids have direct development. Oviparous teredinid species have a free swimming period of 3 to 4 weeks during the larval phase (Turner, 1966) and it was estimated that *Psiloteredo megotara*, and probably other oviparous species, may produce over 100 million eggs in one spawning (Sigerfoos,1908). This long period of permanence in the plankton allow the larvae to be transported to considerable distances by currents (Scheltema,1971).The permanence in the plankton of the larvae of long-term brooders is in contrast much shorter than those of oviparous species (Lebour 1946). Nevertheless, the free swimming period that the larvae stay in the plankton, allows their dispersion by currents or, in later years, also in ballast water (Gollasch, 2002; Shipway *et al.*, 2014). Limnoriids have in comparison with teredinids, much lower fecundity (Cragg *et al*., 1999) and the number of fertilized eggs is much smaller (5-30 depending on species) than that in teredinids. However, the young develop in the brood pouch for 2-4 weeks and are thereafter released into the parental galleries (Eaton and Hale, 1993). During this period, young limnoriids are protected from external adverse conditions by the parents (Thiel, 2003), which probably maximises survival rates. In addition, they can produce 1-3 clutches of eggs in a year, iteroparity, depending on the water temperature (Eaton and Hale, 1993) From the parents tunnels´ they excavate their own perpendicular tunnels, provoking high biodeterioration to the infested wood. The main mean of dispersion of limnoriids in the past was probably in the hull of wooden ships (Carlton, 1999). Nowadays however their dispersal is probably achieved by rafting in floating wood, similarly to what was described by Miranda & Thiel (2008) for algae boring limnoriids. It is also possible that limnoriids can be transported in ships either in ballast water (Carlton, pers. com.) or in the sea-chests, although up to now they have never been observed either in ballast water or sea-chests (Borges *et al.*, in press),

5. Conclusions

The adequate choice of wooden materials for maritime construction as well as the development of protection methods for wood destined to marine construction should, ideally, be based on knowledge on borer hazard, in the areas where the construction is going to take place. However it is well known that the activity of marine wood borers is spasmodic, showing year on year variation. To obtain a better marine-borer hazard `resolution´ in Europe, a more detailed survey is needed, particularly in the Mediterranean and Black Seas where only two and one site were surveyed, respectively. In addition, to obtain data that covers year on year variation on test sites, test panels should be deployed for a number of years. The present study, although limited to only one year can provide, nevertheless, an indication of the borer hazard in several sites covering a wide range of environments in European coastal waters.

The present results show that borer hazard varies with site, due to the type of bores present and with environmental conditions. In the majority of sites (nine) the borer hazard was very high (above 3) considered severe attack according to (EN 275, 1992). In most sites teredinids posed a higher hazard than limnoriids. However in the Terceira Azores and Olhão, Portugal the severity of attack of *Limnoria tripunctata* (4) was higher than that of teredinids. Therefore, limnoriids should not be underestimated as their activity can also be very destructive, as shown in this work.

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