Durability and Protection of Timber Structures in Marine Environments in Europe: An Overview

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Timber structures in marine applications are often exposed to severe degradation conditions caused by mechanical loads and wood-degrading organisms. This paper presents the use of timber in marine environments in Europe from a wood protection perspective. It discusses the use of wood in coastline protection and archeological marine wood, reviews the marine borer taxa in European waters, and gives an overview of potential solutions for protection of timber in marine environments. Information was compiled from the most relevant literature sources with an emphasis on new wood protection methods; the need for research and potential solutions are discussed. Traditionally, timber has been extensively utilized in a variety of marine applications. Although there is a strong need for developing new protection systems for timber in marine applications, the research in this field has been scarce for many years. New attempts to protect timber used in marine environments in Europe have mainly focused on wood modification and the use of mechanical barriers to prevent colonization of marine wood borers. The importance of understanding the mechanisms of settlement, migration, boring, and digestion of the degrading organisms is key for developing effective systems for protecting timber in marine environments.

Keywords: Marine wood borers; Use Class 5; Coastline protection; Limnoria spp.; Teredinids; Wood protection

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INTRODUCTION

Timber Structures in the Marine Environment

Timber structures in marine applications are exposed to harsh environments in the intertidal and subtidal zones (Tsinker 1995). These diverse environments include a wide range of deteriorating organisms such as bacteria, decay fungi, and marine wood borers (Oevering *et al.* 2001). In addition to the resistance to wood-degrading organisms, high mechanical resistance of marine structures, in particular on the shoreline, is required due to high mechanical loads caused by the recurrent impact of waves and shingles, sand, ice, and other solid fragments transported by the waves, wind, and tide. Groynes and revetments represent two of the most challenging applications for wood materials, because they need to withstand both high mechanical loads and the attack of biological organisms. Abrasion resistance is needed as well, which is typically achieved by using dense tropical hardwoods. Timber in the marine environment is, in contrast to other construction materials such as concrete and steel, only insignificantly affected by the salt content (Cragg 1996). In spite of its accessibility to deteriorating organisms, timber is an attractive construction material for decision makers for marine environments, not the least due to its renewable character, resilience, favorable strength to weight ratio, but also flexibility in fabrication and repair (Williams *et al.* 2005).

The use of timber in port constructions and jetties

Wharves and jetties are often constructed of concrete and steel, which are capable of withstanding higher loads imposed by contemporary shipping. Although smaller structures may still employ timber, concrete will keep its importance for port constructions and remain the dominant material in the future (Alexander and Nganga 2016). However, marine structures made from steel or reinforced concrete are greatly affected by chloride ion, which leads to corrosion (Sosa *et al.* 2011). In marina design, where the structures often are designed to float, timber is still preferred for its aesthetics, pedestrian comfort, and ease of repair (Williams *et al.* 2005). These timber structures mainly need to withstand the attack of biological organisms, unlike groynes and revetments.

The legal situation concerning wood preservatives in Europe

The use of biocides and preservative-treated wood in Europe is mainly regulated by the Biocidal Products Regulation (BPR) (EU Regulation 528/2012 2012) and the Construction Products Regulation (CPR) (EU Regulation 305/2011 2011). The BPR regulates the biocides on the market and harmonizes these products for the European market. This includes both the active substances and treated products. The CPR only applies to specific product groups intended for construction that a current European Harmonized Standard exists. In addition, labels are issued regarding the quality and the performance of preservative-treated timber for the different European countries (Kutnik *et al.* 2017; Stephan *et al.* 2017). Referring to current standards, there are no preservatives used in Europe that are approved for use in the Use Class 5 (marine) category (EN 335 2013).

Wood protection in Use Class 5

Different service situations or environments for wood products are expressed as use classes from class one to five in the respective European standard (EN 335 2013). These use classes define the application of wood from indoor to outdoor applications, such as wood and wood-based products not exposed to the weather and wetting (Use class 1), under cover and not exposed to the weather, but with occasional wetting (Use class 2), above ground and exposed to weather (Use class 3), in direct contact with ground and/or fresh water (Use class 4), and permanently or regularly submerged in salt water (Use class 5). Wood protection systems with CCA (copper, chromium, arsenic), creosote, or double impregnations of both CCA and creosote are widely used around the world in the European Use Class 5/Australian Hazard Class 6 (AS1604.1 2012; SANS 10005 2016; AWPA 2017). However, due to the harsh environment in marine applications, retention requirements in Europe for CCA in Use Class 5 (40 kg/m^3) were 10 times higher than in Use Class 3 applications (4.0 kg/m^3, situation where wood is exposed to weather). A slightly lower difference was prescribed for creosote (128 kg/m^3 in Use Class 3, and 400 kg/m^3 in Use Class 5 applications) (Wilkinson 1979). However, the highly effective preservative CCA has been banned in Europe since 2004, and the industrial use of creosote faces tighter restrictions since 2013, while consumer use of creosote has been banned since 2003 due to the ecotoxicity of these substances and for being harmful to human health. Today, no wood preservative is approved for application in seawater in Europe. Humar *et al.* (2013) showed that in the field trials in the Northern Adriatic Sea, the performance of biocide-treated wood samples improved with increasing concentration of the biocide. The Alkaline Copper Quaternary (ACQ)-based wood preservatives were assessed at this study site. To ensure a similar protective efficacy for copper-treated wood, as previously reported for CCA-treated wood, high retentions of active ingredients were shown to be required. A five-year study in port Koper in Slovenia indicated that wood should retain approximately 70 kg/m^3 of ACQ-based copper preservatives after impregnation to enable sufficient durability. This concentration is six times higher than the retention approved for Use Class 3 applications. However, such high retentions lead to rather high concentrations of active ingredients in the leachates at least during the beginning of the exposure. Hence, it is very unlikely that these ACQ-based preservatives will be approved due to eco-toxicological regulations. ACQ-based preservatives, are discussed for their use in marine environments and underwent first monitoring studies, *e.g.*, at the German Baltic Sea shore (Hellkamp 2012). It is unlikely that these protection measures withstand harsh coastal conditions due to abrasion, which could easily wear away the treated outer zones of the timber.

Fig. 1. Portfolio of abiotic and biotic hazards relevant for marine structures (Illustration: Treu *et al.* 2018)

Requirements for Material Properties of Timber in the marine environment

In a survey on the perception of material attributes for timber serving in the marine environment, such as timber pilings or groyne planking in the UK, the respondents identified the resistance to marine wood borers as the most important material property, followed by strength, resistance to impact, abrasion, and fouling by marine organisms (Williams *et al.* 2005). The desired material properties of timber for use in the marine and fluvial environments can be summarized as being: high density, to withstand the scouring action of the waves; strong, especially in bending; high stiffness to withstand impact; high durability, against fungal attack and against marine wood borers; treatable, in case of non-refractory wood species with low natural durability; and large in dimension, necessary if construction is in areas with large differences in water level due to tide. The different biotic and abiotic factors are summarized in Fig. 1.

Aim of Overview

This paper presents: 1) the use of timber in the marine environment in Europe from a wood protection perspective, 2) a compilation of the most relevant literature with an emphasis on new wood protection methods, and 3) potential solutions and the need for future research that can contribute to the durable use of wood in marine applications.

MARINE ORGANISMS ATTACKING TIMBER

Wood borers consume submerged wood in the sea and fulfil an important ecological role in the turnover of organic material. Untreated anthropogenic wood structures are attacked in the same manner as natural wood debris. The most important and accurate work in terms of comprehensive and systematic overview of wood borers, Limnoriidae and Teredinidae, was conducted in the 1950s and 1960s, respectively (Menzies 1957; Turner 1966). Marine wood borers include *Bivalvia* (Teredinidae and Xylophagaidae), *Isopoda* (Limnoriidae and Sphaeromatidae), and *Amphipoda* (Cheluridae). In Europe most wood-boring bivalves belong to the Teredinidae, but species of the Xylophagaidae, such as *Xylophaga dorsalis*, also have been reported as present near the sea bed in Europe (Santhakumaran and Sneli 1978). Attack by teredinids is difficult to detect with the naked eye, but a magnifying glass can more easily display entrance holes of larvae. The degree of attack is usually analyzed by x-ray, when non-destructive evaluation is required, such as computer-aided tomography (Charles *et al.* 2018), but can also be investigated by density measurements or strength determination as well as wood sample preparation and borer species identification (Turner 1966).

The European wood-boring Crustacea belong to the Limnoriidae and Cheluridae families. Their attack pattern is shaped by their tunneling activities on the wood surface and is usually easier to detect with the naked eye compared with shipworm attack. In combination with wave action in the tidal zone, wooden piles will show an hour-glass shape. More recent reviews on potential attacking wood borers in the marine environment is given for Limnoriidae by Cookson (1990) and Cragg (2003) and for Teredinidae by Distel (2003), and Voight (2015), where the authors provide a current state of knowledge about biogeography, competition and predation among wood borers and the role of bacterial endosymbionts. In addition, Table 1 gives an overview of wood borer species and their occurrence in European waters.

In addition to wood borers, obligate wood-degrading marine fungi are able to degrade wood. These fungi occur solely in saline waters or close to river mouths. Furthermore, facultative marine fungi, which are usually found in freshwater and terrestrial environments, are also able to grow in the saline marine environment. Their ability to degrade lignocellulose make them important organisms that need to be taken into account when using timber in seawater (Hyde *et al.* 1998). Bacterial and soft-rot decay also occur on wood in marine applications and can cause surface erosion, degradation, and deterioration (Daniel and Nilsson 1998). Other fouling organisms, *e.g.*, barnacles, which can attach to the wood and other surfaces, are especially feared in relation to the protection of boat hulls (Wiegemann 2005).

Table 1. Marine Wood-boring Species in Europe and Their Salinity and Temperature Requirements

Family	Species	Salinity, SSS (PSU)	Temperature SST (°C)	Sampling site	Reference
Teredinidae	*Teredo navalis* (Linnaeus)	7 to 35	0 to 30	Kristineberg Marine Biological Station-Sweden; Roskilde, Denmark; Foresterei Timbrook, Germany; Kiel, Germany; Haren, Netherlands; Yerseke, Netherlands; Berder, France; Golfe du Morbihan, France; Baie de Villaine, France; Toulindac, France; Rovinj, Croatia; Amasra, Turkey; Mersin, Turkey	Borges *et al.* (2014b)
	Psiloteredo megotara (Hanley)	27 to 37	1 to 25	Trondheim Fjord, Norway	
	Nototeredo norvagica (Spengler)	17 to 39	2 to 39	Trondheim, Norway; Toulindac, France; Berder, France; Penerf, France; Banyuls-sur-Mer, France; Mersin Bay, Turkey	
	Bankia carinata (Gray)	10 to 30	35 to 40	Rovinj, Croatia; Mersin Bay-Turkey	
	Lyrodus pedicellatus (Quatrefages)	33 to 37	7 to 24	Portsmouth, England; Golfe du Morbihan,	

				France; Rovinj, Croatia; Praia da Vitória, Portugal; Lisbon, Portugal; Mosteiros, Portugal; Olhão, Portugal; Mersin Bay, Turkey	
	Lyrodus mersinensis	n.d.	n.d.	Mersin Bay, Turkey	Borges and Merckelbach (2018)
	Teredo bartschi (Clapp)	33-40, 6-35[1]	15-30, 16-32[1]	Olhão, Portugal; Mersin Bay, Turkey	Borges *et al*. (2014b) Borges *et al*. (2014c) Hoagland (1986)
Xylophagaidae	*Xylophaga dorsalis* (Turton)	35 to 39	3 to 20	N. E. Atlantic. From N. Norway (Lofoten) to the Mediterranean	Knudsen (1961).
	Xylophaga nidarosiensis (Santhakumaran)	n.d.	n.d.	-	-
	Xylophaga noradi (Santhakumaran)	n.d.	n.d.	-	-
	Xylophaga praestans (Smith)[2]	35	4-18	Trondheimsfjord, Norway; Durham, England[2]	Knudsen (1961)
Limnoriidae	*Limnoria quadripunctata* Holthuis	30 to 37	4 to 25	Portsmouth, England; Golfe du Morbihan, France; Baie de Villaine, France; Banyuls-sur-mer, France; Viana do Castelo, Portugal; Tagus Estuary, Portugal; São Miguel, Azores	Borges *et al.* (2014a)
	Limnoria lignorum (Rathke)	17 to 36	1 to 20	Reykjavik, Iceland; Trondheim, Norway; Kristineberg Biological Station, Sweden;	

				Yerseke, Netherlands	
	Limnoria tripunctata (Menzies)	31 to 39	11 to 30	Aveiro, Portugal; Terceira, Azores; Tagus Estuary, Portugal; São Miguel, Azores; Olhao Harbour, Portugal; Mersin Bay, Turkey	
Cheluridae	*Chelura terebrans* (Philippi)	n.d.	n.d.	-	-

Note: The different species were found either in wood panels or in fixed wooden structures in the described areas usually at a depth of 2-3 meters; n.d. = no data; SSS = Sea Surface Salinity; SST = Sea Surface Temperature; [1]data reported for larvae from New Jersey, USA; [2]usually found in greater depths.

Distribution of Wood borers

Comprehensive studies on the biogeography of both wood-boring crustaceans (Limnoriidae) and bivalve wood borers (Teredinidae) have been performed in European coastal waters. These studies showed the diversity of established species and their past and recent distribution (Borges *et al.* 2014a,b). It is evident from studies on wood boring limnoriid species that *Limnoria quadripunctata* and *L. tripunctata* have extended their range in European waters, while the distribution of *L. lignorum* appears to have declined (Borges *et al.* 2014a). Studies on the occurrence of teredinids in European waters show that some species extend, contract, or compete in the same distribution range which each other. Depending mostly on their high tolerance to water temperature and salinity, the wood borer species *Teredo navalis* and *Nototeredo norvagica* show a wide distribution area in Europe. However, the reproductive patterns, in particular the release of short-term or long-term living larvae (larviparous) in comparison with oviparous species, which lay eggs with little or no other embryonic development, can be responsible for a competitive advantage (Borges *et al*. 2014b). The distribution of *Teredo navalis* and *Lyrodus pedicellatus* in European waters should be monitored due to their destructive capacity, as well as the spreading of alien species such as *Teredo bartschi* and *Teredothryra dominicensis* (Borges *et al*. 2014c). Monitoring the activity of wood borers is important and needs to be continued to predict the service life of wood structures in marine environments.

Wood borers in Northern coastal waters

The distribution of shipworms is not limited to warmer geographical areas. They can occur in seawater temperatures ranging from the Mediterranean areas to the Arctic Circle. The most common coldwater shipworm species along the west coast of Norway is *Psiloteredo megotara*, which is found even north of Finnmark (Knudsen 1974). The spread of the different species along the coast of Norway is otherwise not documented because most surveys have been based on limited areas along the coast. However, it can be noted that *Nototeredo norvagica* is found along the coast of north and western Norway (Nair 1962). Santhakumaran and Sneli (1984) found *Psiloteredo megotara*, *Xylophaga dorsalis*, *Xylophaga praestans*, *Xylophaga nidarosiensis*, and *Xylophaga noradi* in the Trondheimsfjord. Dons (1948) stated that in Trøndelag, *N. norvagica* occurs especially in the archipelago, while *Psiloteredo megotara* is dominant in the fjord. According to Dons

(1948), *Teredo navalis* is not established north of Bergen. A comprehensive study on the different fouling and wood-boring organisms in the fjord of Trondheim in western Norway was performed by Santhakumaran and Sneli (1978, 1984). Since then, no research has been published on wood protection in marine environments in Norway.

Wood borers along the Swedish coast have been extensively analyzed during the last decade. Despite an increase in surface sea water temperature, no significant increase in abundance of *Teredo navalis* at several test sites at the Swedish west coast was observed. A decreased abundance of teredinids towards the Southern part of Sweden's West coast was found. The hypothesis of shipworms having expanded their range into the Baltic Sea could not be proven (Appelqvist *et al.* 2014; Appelqvist 2015).

CHANGING CONDITIONS IN MARINE APPLICATIONS

Climate Change and Sea Level Rise

A recent study by Nerem *et al.* (2018) on climate change-driven sea level rise predicts an accelerating rate, which highlights the significance of the problem and the importance for coastal protection. The reported sea level rise in combination with extreme weather events will lead to increasing costs for coastal protection. It is believed that England and Wales invest around £500 million per year in flood and coastal defense engineering (Simm and Masters 2003). Newer figures from the Environment Agency in the United Kingdom reports bids for contract works with an estimated total value of £220 million (Environmental Agency 2018).

A report on sea level change in Norway predicts a fall in relative sea level in the Oslofjord inlet and in the middle of Norway, but a rise in relative sea level for the Norwegian coast in the South and West and for the northernmost tide gauges (Simpson *et al.* 2015). Correcting for the glacial isostatic adjustment (GIA), the sea surface height rates are positive and close to the global average rates.

Coastline Protection

Coastal erosion is an increasing problem that is influenced by accelerated sea level rise (Leatherman *et al.* 2000), changes in sediment supplies, storms, river delta subsidence, and human impact (Eurosion 2002). An overview of coastal erosion patterns in Europe is given in Fig. 2. There are a number of forms of coastal defenses where timber can be included, such as seawalls, revetments, breakwaters, groynes, and dune fencing. Timber is a technically versatile material since it offers a balance between strength, size, durability, workability, and buildability (Crossman and Simm 2004). A coastal protection system consists of a combination of beach and backshore elements such as cliffs, beaches, dunes, and/or artificial defenses that contribute to flood protection and coastal erosion prevention (Hudson *et al.* 2015). A gradual change from hard protection structures, such as groynes, revetments, offshore breakwaters and seawalls, to soft coastal defense techniques, such as artificial nourishment of beach areas, has been observed over the last 60 years. However, such techniques are neither easy to sustain nor well established and vary widely throughout the different European countries (Hanson *et al.* 2002).

One method for hard coastline protection is the use of groynes, which must withstand heavy wave impact and are exposed to longshore drift of shingle or sand. However, timber has an advantageous strength to weight ratio and is versatile and adaptable in design. Timber structures are more easily repaired or extended than concrete structures. Repair on woodpiles for marine applications has been demonstrated by using fiber-reinforced polymer and could fully restore the bending strength of a damaged woodpile. (Lopez-Anido *et al.* 2003).

The increase of coastal erosion is associated with an increase in costs. The following key cost components may need to be considered to estimate the total costs of coastal protection: procurement and design costs, capital construction costs, operation and maintenance costs, monitoring costs, and replacement or decommissioning costs (Hudson *et al.* 2015). For example, timber revetments could be cheaper in capital costs but higher in maintenance costs than rock revetments. Overall, the use of timber is more attractive for the construction of groynes compared with the use of rocks, when costs and environmental issues are considered. When compared to other materials for the construction of piles for groynes, recycled wood is favored due to reasonable service life and low transport costs, but mainly due to ecopoints, a system that assesses wide environmental impacts, material and transport options (Masters 2001; Crossman and Simm 2004).

All European countries that have a coastline are affected by coastal erosion. Altogether, 20% of the coastline in Europe faced serious impacts in 2004, with a large area of retreating zones. Timber can be, or is already used, in the 4,700 km of artificially stabilized coastlines (Salman *et al.* 2004).

A study on global coastal protection considers an investment in protection of the high-populated coastal areas as economically robust, which means these areas would save money investing in protection rather than not protecting their coastline (Lincke and Hinkel 2018).

Changes in the Abundance and Distribution of Wood Borers

Changes in the requirements on timber applied in the marine environment are anticipated not only because of sea level rise and extreme weather events, which threaten the safety of coastlines, but also because of the change in seawater temperature, salinity, and the import of foreign wood-deteriorating species. The increase in salinity due to global warming could enable marine wood borer mollusks of the families Teredinidae and Xylophagaidae, to invade other areas, *e.g.* the waters of Russia and adjacent marine areas where these changes of environmental factors would promote an invasion of wood borers (Iljin 2010). Only a few of the numerous environmental factors are limiting the colonization of new regions by these organisms. These factors mainly include the abiotic ones, such as temperature and water salinity, as well as ice conditions.

While no evidence of the invasion of the Baltic Sea by teredinid recruits was found on the Swedish coast (Appelqvist *et al.* 2014), it is reported that shipworm is spreading within the Southern part of the Baltic Sea, leading to severe problems and economic damages in Denmark, Germany, Poland, and Southern Sweden (Sordyl *et al.* 1998; Borges *et al.* 2014b; Lippert *et al.* 2017). While the abundance of *Teredo navalis* was positively correlated to the surface water salinity, no positive correlation to temperature could be shown. Climate models anticipating a decrease in salinity would affect negatively the abundance of *T. navalis*, in the Baltic sea (Appelkvist *et al* 2014). Tuente *et al.* (2002) reported the occurrence of *Teredo navalis* in the harbors of Bremerhaven at the shores of the North Sea in Northern Germany for the first time in 2002.

A study of *T. navalis* in the southwestern Baltic Sea showed an increased abundance with increased temperatures and salinity. However, high variation in abundance also depending on the evaluation year, made it difficult to explain the factors controlling the settlement. The distribution of this shipworm species could be slightly changed towards the Mecklenburg-Western Pomeranian Baltic Sea coast, where a dramatic increase in the amount of damage in timber structures was observed (Lippert *et al.* 2017).

Economic damage on timber structures caused by marine wood borers accounts for many billion € per year (Saathoff *et al.* 2010). During the last mass occurrence of *Teredo* spp. at the German Baltic Sea coastline, groynes valued at €12.8 million were destroyed in 1993 (State Agency for Agriculture and Environment Middle Mecklenburg 2017). Invasive species have also been found in the Mediterranean Sea, which is of considerable concern if species are tropical because they are particularly destructive and degrade wood more rapidly (Shipway *et al.* 2014; Borges *et al.* 2014c). The spreading of shipworm could be avoided by removing wooden structures along the coastlines (Appelqvist *et al.* 2015). However, this is a counterproductive solution if an increased use of wood is desired. In addition, driftwood is a significant energy source for different organisms in the marine ecosystem and elimination of driftwood is hardly possible nor desirable.

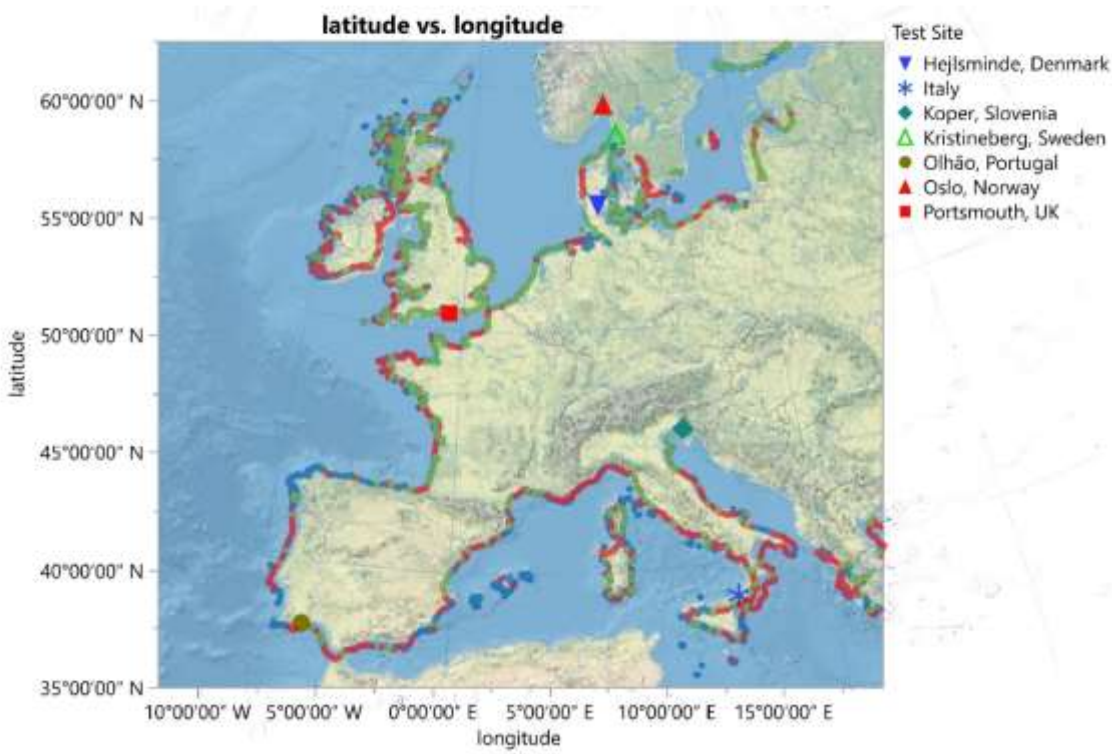

Fig. 2: Permanent marine test sites for wood treatments and overview of coastal erosion patterns in Europe according to the European Environment Agency (2016); (aggradation in green, erosion in red, stable conditions in blue)

RESEARCH ACTIVITY IN RECENT YEARS

The research done on wood-boring organisms in the marine environment is mostly related to novel solutions for the protection of wood, tropical wood species with high natural durability, the attack on waterlogged archaeological wood, and the abundance and distribution of these organisms on different areas of the world.

Research on Wood Protection and New Solutions

New attempts to protect wood in the marine environment in Europe focus mainly on wood modification (Klüppel *et al.* 2014; Lopes *et al.* 2014; Janus *et al.* 2018; Klüppel 2018; Westin *et al.* 2006, 2016). A wood modification protects timber from biological degradation by using non-biocidal mechanisms. Wood treated with 1,3-dimethylol 4,5-dihydroxy ethylene urea (DMDHEU), methylated-methylol-melamine resin (MMF), acetic anhydride, or furfuryl alcohol provided resistance to marine wood borers (Klüppel *et al.* 2014; Westin *et al.* 2016). However, the currently available wood modification technologies are still essentially niche products that come at a cost, and this restricts their use to higher value products. Some of these new treatment methods, such as thermally modified wood, give a brittle wood material or they only protect the wood material for a short period of time when exposed to the marine environment. In addition to wood preservatives and wood modification systems, protection of timber structures in seawater has been achieved using metals, concrete, plastic, and coatings as physical barriers (Findlay 2013). The performance of physical barriers is limited by corrosion, cracking, or breaking, which will allow marine wood borers access to the timber within. Other treatment solutions that focus on the protection of full-size wooden poles by wrapping geotextiles around them were found to provide sufficient protection against shipworm (Saathoff *et al.* 2010; Müller 2014). However, geotextiles are believed to allow fungal decay in untreated wood. Furthermore, the wood borer *Teredo* spp. is even described as a problem in subsea umbilical, which are high-tech cable connections often used by the oil and gas industry in subsea applications (Parkes and Keeble 2016). The authors provide no direct evidence that the destruction in modern cables is due to teredinids. It is more likely that species from the Pholadidae are the responsible organisms. In fact, Xylophaga species are described to be found in the insulation of submarine telegraph cables and feed entirely on plankton (Purchon 1941).

It is imperative to know the mechanisms of settlement, boring, and digestion of the degrading organisms to develop effective ways to protect timber in marine environments. The first settlement of larvae on the wood surface is an important phase of the life cycle of Teredinidae, but very little is known about the cues and processes that promote this settlement. Shipworm larvae are attracted to wood by chemical cues, but only to a limited degree. These chemical cues are described to be effective during or after the attachment of the larvae, or very close to the wood substrate. Therefore, the larval settlement is not entirely random (Toth *et al.* 2015).

In contrast to the aim of avoiding larval settlement of shipworm larvae, researchers have worked on the optimal recruitment of larvae to substrates for commercially used bivalve species such as pearl oysters (Wassnig and Southgate 2012). This study is an example of how settlement can be promoted by manipulating the substrate. The opposite effect, preventing substrate settlement, could be key to wood protection measures in the future. More research in the field of the marine wood borer settlement will make for a better understanding of the settlement strategies. This gained knowledge will enable the development of new protection systems, which make timber unrecognizable for boring organisms.

Once the wood-boring organisms detect the wood material, they need to attach to the surface. Studies on barnacle attachment demonstrated the diversity of adhesive chemistry within barnacle species (Wiegemann and Watermann 2004; Wiegemann 2005; Wiegemann *et al.* 2006; Jonker *et al.* 2015). However, since the knowledge on barnacle attachment is not transferable to wood borer settlement and cues for settlement are species specific, more research could investigate species-dependent wood borer settlement. Further research should result in non-toxic fouling prevention systems for the marine environment. However, new antifouling strategies need to include both the chemical concepts, such as surface energy, and the physical concepts, such as surface roughness and fluid hydrodynamics (Magin *et al.* 2010).

Several authors (Miller 1924; Board 1970; Roder 1977; Dorgan 2015) comprehensively describe the burrowing and boring methods, as well as how an increase in hardness of wood will contribute negatively to burrowing and boring. However, in forced feeding laboratory tests on *Limnoria quadripunctata*, this correlation could not be seen when testing a range of wood species (Cragg *et al.* 2007). The same organism was tested using sodium silicate-treated wood, resulting in leaching of the impregnated, active substance (Serpa 1980). Laboratory trials need to take into account the potential toxic effect of the leachate. The mandibles of *L. quadripunctata* were damaged in a laboratory test on wood samples impregnated with two mineralizing-based solutions, suggesting that abrasiveness and hardness of the wood had been increased (Bowen *et al.* 2017). Unfortunately, it is not mentioned in the study which kind of mineralizing solutions were used. A potential method worth testing is the treatment of wood with calcium carbonate or barium sulphate to increase the hardness of the outer wood layer and to disguise the wood material for the marine wood borers (Merk *et al.* 2015, 2016, 2017). These strategies could work in estuaries, port facilities, and sheltered environments. However, they are unlikely to work in coastal situations due to abrasion.

Feeding and digestion of wood by borers has been a research focus in recent years (King *et al.* 2010; Betcher *et al.* 2012; Kern *et al.* 2013; Eriksen *et al.* 2015; Sabbadin *et al.* 2018). This is vital information that needs to be utilized in further research on wood protection. Several papers describe the degradation pattern from a marine zoology perspective or the enzymatic degradation related to the biomass utilization aspect (Sabbadin *et al.* 2018). Minimal research has been focused on understanding these degradation mechanisms. The endosymbiotic bacteria in the gills of shipworm have been proposed to assist the shipworm host in cellulose digestion and have been shown to play a role in nitrogen fixation (Distel *et al.* 2002; Elshahawi *et al.* 2013; O'Connor *et al.* 2014).

A second generation of wood modification that includes optimized modification systems or a combination of treatments, may have the potential for long-term use in the marine environment. Furthermore, these new products could either fulfill a wide range of performance criteria or be tailored for a certain type of application. In addition, research needs to be 'borer species' related and needs to focus on the mechanisms of settlement, boring, and digestion of the degrading organisms.

The Use of Tropical Wood Species in Marine Applications

Durable tropical wood species have been used for different applications in seawater contact and building of marine structures often stick to a limited number of well-established wood species. There are a number of tropical wood species and lesser-known timbers with comparable resistance to timbers currently used for marine construction (Santhakumaran and Sneli 1978; Rosenbusch *et al.* 2006; Borges *et al.* 2008; Sen *et al.* 2009; Palanti *et al.* 2015), but they often face difficulties in being accepted by the users. The suppliers of lesser-known species must increase the end user's knowledge of their products (Williams *et al.* 2005). However, the use of well-established tropical wood species is increasingly diminishing because their production is associated with illegal logging, deforestation, and socio-political problems in the respective origin countries. Evidence of a legal and sustainably managed source is required when importing tropical timber. In addition, the costs for tropical timbers are on average three times higher compared to home-grown Scots pine (Saathoff *et al.* 2010). Other European wood species, such as black locust (*Robinia pseudoacacia*), sweet chestnut (*Castanea sativa*), and English oak (*Quercus robur*), have been used for groynes but suffered from premature failures. All of the above listed European wood species were completely degraded by wood borers after 6 to 8 months of exposure in Port Koper, Slovenia, by *Teredo* spp., *Lyrodus* spp., and *Limnoria* spp. According to the European standard EN 350 (2016), none of these wood species were classified as resistant against marine wood borers as was none of the European species listed. However, a study performed by Norman (1976) on different Swedish wood species showed that barked aspen roundwood was attacked at a lower rate than debarked roundwood, and the attack occurred only through the cutting edges. However, in a more recent study, debarked aspen was heavily attacked after 4 months in different test sites within the Oslofjord inlet (Treu *et al.* 2018).

Research on Waterlogged Archaeological Wood

Extensive research has been conducted on waterlogged archaeological wood in marine and terrestrial environments (Björdal *et al.* 1999; Blanchette 2000; Christensen *et al.* 2006). Wood degradation in marine sediments is mainly restricted to bacterial decay due to the absence of oxygen. A study on wood samples exposed at different distances above and below the seabed revealed a complete decomposition of wood exposed above seabed, while increased depth of buried wood samples in the seabed showed decreasing decay (Björdal and Nilsson 2008).

The Swedish wooden warship Vasa, which sank in the harbor of Stockholm in 1628, has been exposed close to the seabed for over 300 years before it was rediscovered in 1956 and salvaged in 1961. After placing the ship in a temporary museum, the hull was sprayed with polyethylene glycol (PEG) until 1979. After a drying period, the ship was moved to the Vasa museum in 1990 for permanent display. Undertaken research on the Vasa ship was related to various conservation issues including measures against chemical, physical, and biological degradation (Sandström *et al.* 2003; Fors and Sandström 2006; Lindfors *et al.* 2008). More ship wrecks that have withstood exposure in marine environments for centuries and have been subjected to conservation and related research were the ‘Mary Rose’ in Portsmouth (Squirrell and Clarke 1987; Mouzouras *et al.* 1990; Sandström *et al.* 2005) and the ‘Bremen Cog’ displayed in Bremerhaven (Hoffmann 2001). Nevertheless, the overall number of well-preserved shipwrecks and other wooden artefacts from the sea is comparatively small due to the harsh environmental conditions and aggressive organisms present.

Research on the waterlogged archaeological wood showed that the extent of remaining cellulose had an influence on the attack by shipworms. Areas in the wood with insufficient cellulose were not attacked, which makes protection measures unnecessary if the state of preservation in the wood does not provide enough nutrients for shipworms (Eriksen *et al.* 2015).

Research Activities on Marine Applications in Recent Years

The protection of wood in the marine environment has traditionally been a research topic for The International Research Group on Wood Protection (IRG-WP). A joint meeting of IRG-WP and COIPM (Comité International Permanent pour la Recherche sur la Preservation des Materiaux en Milieu Marin) resulted in the Marine Working Group being a formal part of IRG-WP (Eaton 1977). Cragg (1986) gave a comprehensive review on marine biodeterioration at the IRG-WP conference in 1986, which included relevant papers from an international conference from the same year in India. An updated version of the different Limnoriidae can be found in the IRG-WP article of Cookson (1990). In addition to the research on individual wood borer species, the different stages of wood fragmentation by the different wood borers has been described (Nishimoto *et al.* 2015), as well as the rate of wood material consumption (Charles *et al.* 2018).

Many scientific publications from the last 20 years report mostly on the performance of well-known and established treatments of timber, either preservative or modification systems, and the different wood treatments or wood species tested in marine field sites in different parts of the world or in the laboratory. However, little is presented on the mode of action of either the protection systems or the biology of the different organisms of wood borers (Barnacle 1990), and only one paper discusses a novel wood treatment, based on mineralization, which is not described in detail by the authors (Bowen *et al*. 2017).

The authors believe that the research focus should be shifted towards finding out how, when, and why the different species of wood borers attack. The number of scientific papers on the topic in the last 20 years does not reflect the importance of the problem. In fact, the problem is urgent, as established effective treatments are no longer available for use in the marine environment in Europe.

Table 2. Permanent Marine Test Sites in Europe

Test Site	Coordinates	Wood-boring Organisms	Institution and Reference Person
Kristineberg, Sweden	58°15'00.3"N 11°26'42.9"E	*Teredo navalis*	RISE, Mats Westin
Oslo, Norway	59°36'57.5"N 10°39'03.7"E	*Teredo navalis*	Norwegian Institute of Bioeconomy Research (NIBIO), Andreas Treu
Koper, Slovenia	45°33'40.2"N 13°44'21.0"E	*Teredo navalis, Limnoria sp.*	University of Ljubliana, Miha Humar
Hejlsminde, Denmark	55°21'40.7"N 9°36'01.1"E	*Teredo navalis*	University of Goettingen, Christian Brischke
Olhão, Portugal	37°01'37.2"N 7°50'28.068"W	*Lyrodus pedicellatus, Teredo bartschi, Limnoria tripunctata*	Sagremarisco, John Icely
Portsmouth, UK	50°47'40.5"N 1°01'48.1"W	*Limnoria quadripunctata,Lyrodus pedicellatus, Teredo navalis, Chelura terebrans*	University of Portsmouth, Simon Cragg
Italy	38°12′1.00″N 15°33′52.00″E	*Teredo navalis*	(Palanti *et al.* 2015)

Marine Test Sites in Europe

A comprehensive study has been performed on the distribution and abundance of different wood-boring species in Europe (Borges *et al.* 2014a, 2014b). However, the described locations were surveyed only for a limited period (one year) and in other cases, borers have been observed during *ad hoc* site inspections. Nonetheless, there are a few sites that have been monitored over a long-term period, thus providing important information on marine wood-boring organisms (Table 2 and Fig. 2). One example is the occurrence of wood borers in the Oslofjord in Norway (Treu *et al.* 2018), which has only been reported earlier by Jones *et al.* (1972).

Researchers in Sweden have been conducting tests in marine environments continually for over 15 years. Their field site in Kristineberg, Sweden has been used for many kinds of projects in the past (Westin *et al.* 2006, 2016). Different chemically modified wood has been tested at the Danish test site, Heijlsminde, during the last ten years (Gellerich *et al.* 2018). Knowledge of the distribution and occurrence of the various species of marine wood borers is essential. Therefore, new permanent test sites are needed where a testing regime can be in service and maintained over many years.

CONCLUDING REMARKS

This review on recent research activities on the protection and preservation of timber structures in the marine environment led the authors to the following conclusions.

Timber structures in the marine environment require protection against both biological organisms and mechanical forces. The use of timber in marine applications competes with the use of concrete and steel. In addition, no wood preservative is approved for marine applications in Europe. Viable alternatives to the banned wood preservation systems and some tropical wood species need to be found if timber wants to play a bigger role in marine applications. The requirements for not only efficacy against wood-degrading organisms, but also for no harmful side effects for non-target organisms must be met by new methods of wood protection.

Lesser known tropical wood species are difficult to market due to the lack of reliable test data on their performance, especially strength properties. More research on the properties of tropical wood species from sustainable forestry would contribute positively to the use of wood in marine structures.

Coastline protection is an increasing problem and will lead to higher costs in the future. Timber used for coastline protection needs to be fit for purpose in a harsh environment. Changes in salinity and temperature of seawater can lead to the spreading of wood-degrading organisms.

Research activities on the protection of timber structures for the marine environment in Europe have been scarce and do not yet adequately meet the need for novel approaches to the problem of biodeterioration of wood in the marine environment. Recent research on novel wood protection systems for seawater applications is shaped by the idea of preventing settlement on the wood surface or interfering with digestive processes. There is a need to understand more about how and why marine wood borers attack timber and focus more on the different species of degrading organisms and the mode of action. Permanent and temporary test sites would help to monitor species abundance and distribution and thus changes in borer hazards.

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