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ORIGINAL ARTICLE

Bioerosion effects of sea-level rise on the Doge's Palace water doors in Venice (Italy)

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Abstract

The Doge's Palace of Venice (Italy) has on its canal-side large doorways closed by old wooden doors. Originally, the thresholds were built above high-water level to avoid direct contact with the water and the resulting damage caused by physical and biological agents. As a result of sea-level rise and land subsidence during the last centuries, the doors are now exposed to tides and to attack by marine wood-boring invertebrates such as shipworms and gribbles. As a consequence, the bottom rails of the doors were recently in need of substantial restoration, which took into consideration new materials and techniques. In this framework, an in situ experiment was undertaken to test the resistance of some selected wood species to woodboring organisms. A quick assessment protocol, based on the EN 275 standard, was set up to quantify bioerosion according to wood species and elevation above sea level. Both European and tropical wood species were tested. The former include Scots Pine, as a reference, and Larch, Cypress and Oak as traditional carpentry materials. The latter include Azobe, Okan, and Bilinga. All the European species showed high susceptibility to woodborer attack, whereas no damage was recorded on the tropical woods. The collected shipworms belonged mostly to *Lyrodus pedicellatus* and *Teredo bartschi* with some individuals of *Teredo navalis*. The only species of gribble found was *Limnoria tripunctata*. New technical solutions were adopted in the restoration aiming to provide a long service life for the replacements and simplifying the maintenance procedures. Experience, results and solutions are presented.

Keywords Climate change · Cultural heritage · Restoration · Shipworms · Marine woodborers · Wood

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Introduction

Sea-level rise and Venetian wood cultural heritage

Sea-level rise (SLR) is a major effect of climate change to which the coastal zone is particularly vulnerable (IPCC 2014), threatening a number of maritime World Heritage Sites such as Venice (UNESCO 2007; Reimann et al. 2018). The outstanding universal value of Venice and its lagoon is due to the intimate functional connection between the aquatic environment and the urban structure of the City (ICOMOS 1987; UNESCO 2019). In the past, the transportation of people and goods in Venice took place through the intricate network of waterways, the *rii*, so that the main facades of the palaces and the warehouse entrances overlooked the canals.

Large "waterdoors" (*porte d'acqua* in Italian) give access to the palaces from the canals. The thresholds of the doorways were placed above the high-tide level, keeping the wooden doors away from direct contact with the water. Some stone steps led to the water-doors. Pile moorings were placed at both sides of the doorway, allowing moored vessels to follow the vertical movements of the tides. Water-doors can be considered as a peculiar example of maritime Wood Cultural Heritage (WCH) (Kim and Singh 2016).

As a consequence of sea-level rise, the majority of the water-doors are now in permanent contact with water and thus open to degradation by physical and biological agents. The rise of mean sea level in Venice is actually due to a combination of eustasy (i.e., the rise of sea level as an effect of climate change) and subsidence (i.e., the local lowering of the land surface due to natural as well as anthropogenic causes). Relative sea-level rise amounts to about 30 cm since the official Venice Datum was established at *Punta della Salute* in 1872 (Ferla et al. 2007; Trincardi et al. 2016).

In the last century, subsidence produced by groundwater extraction in the nearby industrial area has been added to the natural one. As a result, during the 20th century, 12 cm of elevation has been lost due to eustasy, 4 cm to natural subsidence, and 10 cm to groundwater pumping (Trincardi et al. 2016). The ancient Venetians took as a vertical reference the upper edge of the blackish belt that can be observed along the canal banks, which corresponds to the mean high-water level (Fig. 1). This intertidal belt is formed by the growth of microorganisms, chiefly belonging to the phylum Cyanobacteria, also known as Cyanophyta (colloquially blue-green algae). It is called in Venetian *Comun Marin* (CM, "Marine Common") and was locally marked during the *Serenissima* times by engraving a horizontal line surmounted by a "C" on the canal banks (Rusconi 1983). The sinking of Venice over the last 300 years has recently been estimated to be around 60 cm by comparing the current CM with the CM clearly visible in the "photographic" paintings of the Venetian landscape painters, such as Canaletto and Bellotto, who worked using a *camera obscura* (Camuffo 2001; Camuffo and Sturaro 2003). The bottom step of the stairs was also positioned in accordance with the CM, allowing the reconstruction of sea-level variations occurring before the advent of the landscape painters (Camuffo et al. 2017). These retrospective techniques indicated a possible loss of elevation of about 1.3 m from 1300 to the present day (Camuffo et al. 2017). This evidence matches the results of other scientific studies (e.g., Carbognin et al. 2010).

Bioerosion by marine invertebrates

Marine woodborers excavate tunnels in wood on which they also feed. They include shipworms, which are bivalved molluscs belonging to the family Teredinidae,

Fig. 1 One of the letters "C" with which the Venetians used to identify the *Comun marin*, i.e., the limit of the dark band of cyanobacteria which marks mean high-water level. The "C", that was carved just on top of the CM, is now completely below the current CM, evident just below the stringcourse. The difference gives a measure of the relative sea-level rise (location: *Rio San Severo*)

and peracarid crustaceans such as the Gribbles (Isopoda: Limnoridae) and the Pincher-tail scud (Amphipoda: Cheluridae). The main species of shipworms inhabiting in the lagoon of Venice are *Lyrodus pedicellatus* (Quatrefages 1849) and *Teredo navalis* Linnaeus 1758. Moreover, the non-indigenous species *Teredo bartschi* Clapp 1923 has been recently recorded. The planktic larvae of shipworms settle on the wood at the stage of pediveliger and start excavating tunnels that develop upward following the grain. The entry holes are generally less than a millimeter and are difficult to spot on the wood surface by the naked eye. Then, the tunnels widen in the subcortical zone up to a centimeter in width, quickly compromising the entire artifact (Fig. 2). The main species of woodboring peracarids in the lagoon of Venice are the gribbles *Limnoria tripunctata* Menzies, 1951 and *Limnoria tuberculata* Sowinsky, 1884, and the pincher-tail scud *Chelura terebrans* Philippi, 1839. The damage produced by gribbles has the maximum intensity in the tidal range, with erosion proceeding from the surface inward, eroding progressively the wood producing a characteristic "hourglass" (Fig. 3). These features allow operators to immediately recognize the state of degradation on the poles, replacing them before they collapse and become a danger to navigation. In the case of water-doors, a massive attack was observed within the neap intertidal zone (Fig. 3).

Fig. 2 Section of an Oak pole subjected to shipworm attack. The tunnels follow the grain of the wood upwards and are plastered with a calcareous coating secreted by the molluscs

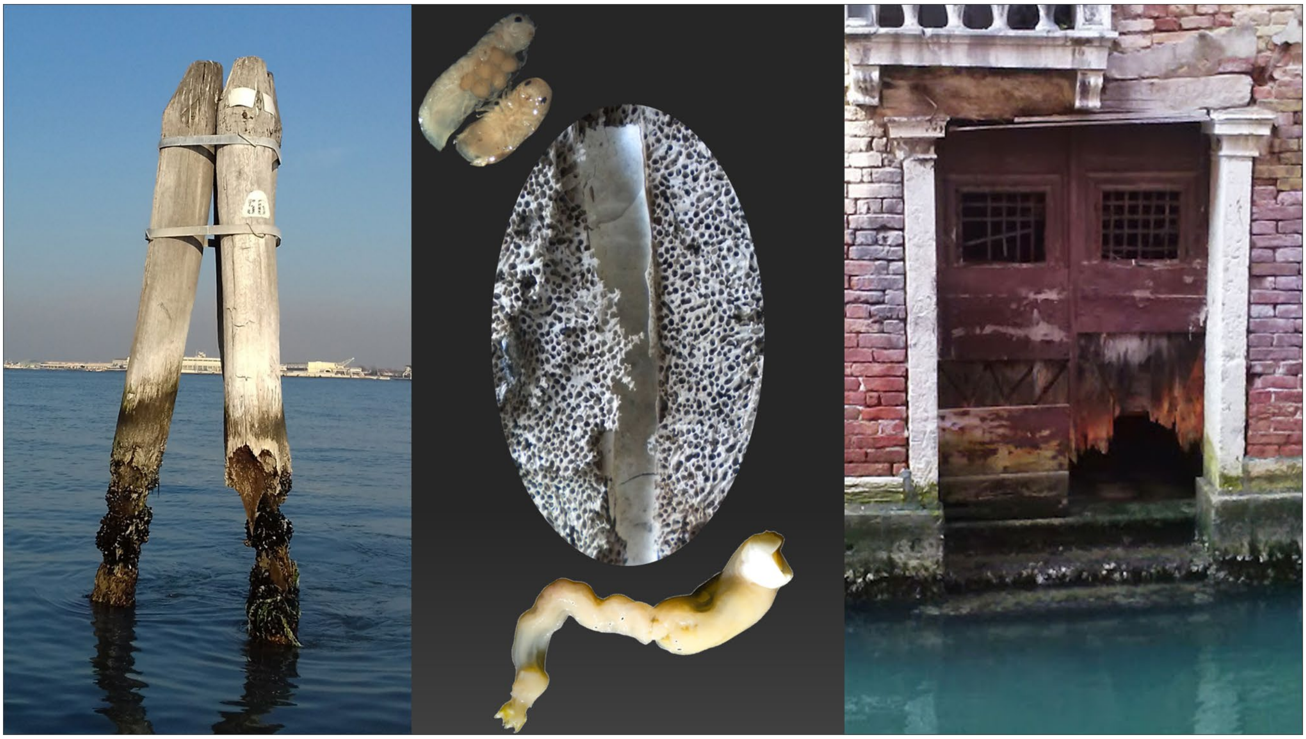


Fig. 3 Effects of the attack of woodborers on posts (left) and on the water-doors (right). The joint action of the two types of woodborers is shown in the central cameo. The gribbles (crustaceans, image superimposed on the right) excavate a dense network of small tunnels while attaching to the wood from the outside whereas the shipworms (bivalves, image superimposed on the right) bore much larger tunnels deep into the wood

Issues and research objective

The *Palazzo Ducale* (Doge's Palace), once the government seat of the *Serenissima* Venetian Republic, has six large water-doors. A short staircase from the *Rio della Canonica* canal gives access to the doorways (Fig. 4).

The current doors were put in place at different times. Two of them date back to the 16th century and four to the 19th century, when they were only occasionally lapped by the tide. With the rising of sea level, the submergence time has increased considerably, exposing the bottom rails to the woodborers attack. The threshold of the water-doors is currently located a few centimeters below mean sea level, the eroded part ending slightly below the CM. At the time of the experiment, the rails showed signs of previous maintenance. Figure 5 compares a picture taken in 1880 by the photographer Carlo Naya (1816–1882) with the current situation. The variation in sea level is indicated by the *Comun Marin* marking the lower step in 1880 and now at the level of the string course.

As of 2011, all doors show severe attack by gribbles up to the hinge, whereas the bottom rail was completely missing due to the destructive joint activity of gribbles and shipworms (Fig. 6a, b). The state of the doors urged the Civic Museums Foundation of Venice (Fondazione Musei Civici di Venezia, FMCV) to set out an extraordinary maintenance and restoration programme. The Foundation raised some questions about the vulnerability to bioerosion of the wood species traditionally used by carpenters, which were a priority choice for restoration, and about the suitability of exotic wood species known to be more durable. Considering that the water-doors are very large (549 cm × 309 cm) and heavy (over 1 ton each), the FMCV was also interested in finding technical solutions allowing easy periodic maintenance of the bottom rail without facing a complete removal of the doors. In 2011, the FMCV started a collaboration with the Italian National Research Council (CNR), through the Institute of Marine Science (CNR-ISMAR) and the Tree and Timber Institute (CNR-IVALSA). Thus, the main objectives of this study have been to test the resistance of selected wood species against the activities of marine woodborers in the site-specific environmental conditions of the *Palazzo Ducale* and to give technical suggestions for improving the performance of the restored doors.

Materials and methods

The assessment of the natural durability against marine woodborers was carried out using a modified version of the EN 275 standard protocol (European Committee for

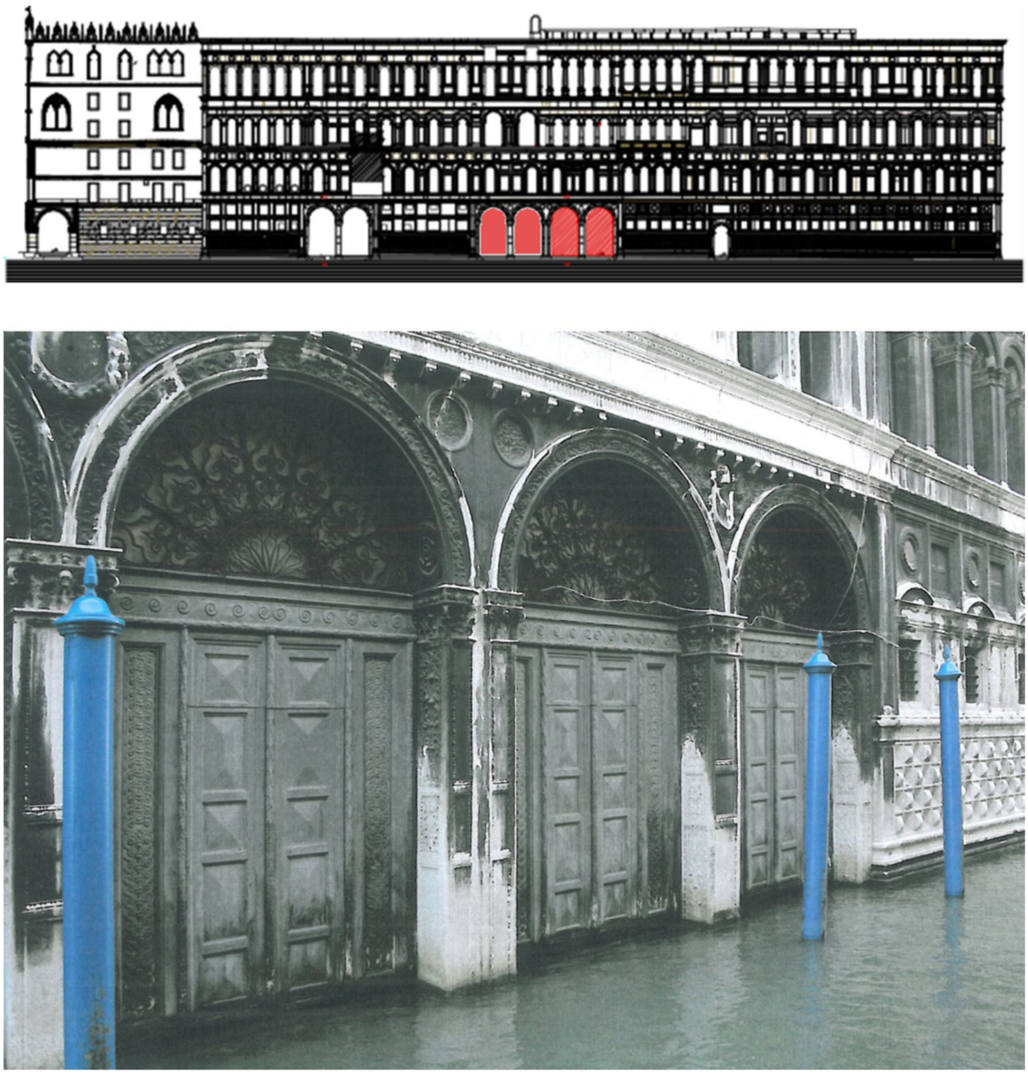


Fig. 4 Façade of the *Palazzo Ducale* facing the *Rio della Canonica*. In red, the position of the doors examined in this study, shown in the picture below

Standardization 1992). According to the original EN 275 protocol, the test should be performed by placing wood test specimens of standard dimensions in seawater, in a subtidal position, for at least 5 years, assessing the attack once a year. Then, the durability class is defined by comparing the test specimens with a reference species (i.e. Scots Pine, *Pinus sylvestris* sapwood) in terms of average service life. The EN 275 was conceived as a field test method for determining the protective effectiveness of wood preservatives against marine borers but it can be also used to evaluate the "natural durability" of wood. In most cases, the term is related to the service life although "natural durability" is defined as "the inherent resistance of wood to attack by wood-destroying organisms" [by EN 350-1 and EN 350-2 (European Committee for Standardization 1994a, b)]. The time taken to fail can be very long for durable species, hence the standard allows the substitution of the reference specimens. Our experience suggests that in temperate lagoons and harbors a single summer of exposure is sufficient to assess susceptibility and resistance of woods; therefore the exposure time was reduced to one season. In this way, what is tested is not the durability sensu EN 275 (service life) but rather the vulnerability or susceptibility, i.e., the inclination to be attacked and damaged. Nevertheless, standard test specimens and Scots Pine as reference species were used to be as close as possible to the original EN 275.

The test specimens were provided by IVALSA. They measured 2.3 cm × 7.0 cm × 16.0 cm with a 25-mm hole in the middle to keep them in place. The total surface of the specimens was 31,998 mm^2 and the volume 235,020 mm^3. Six replicates of heartwood were prepared for each wood species. The wood used was free from defects such as cracks,

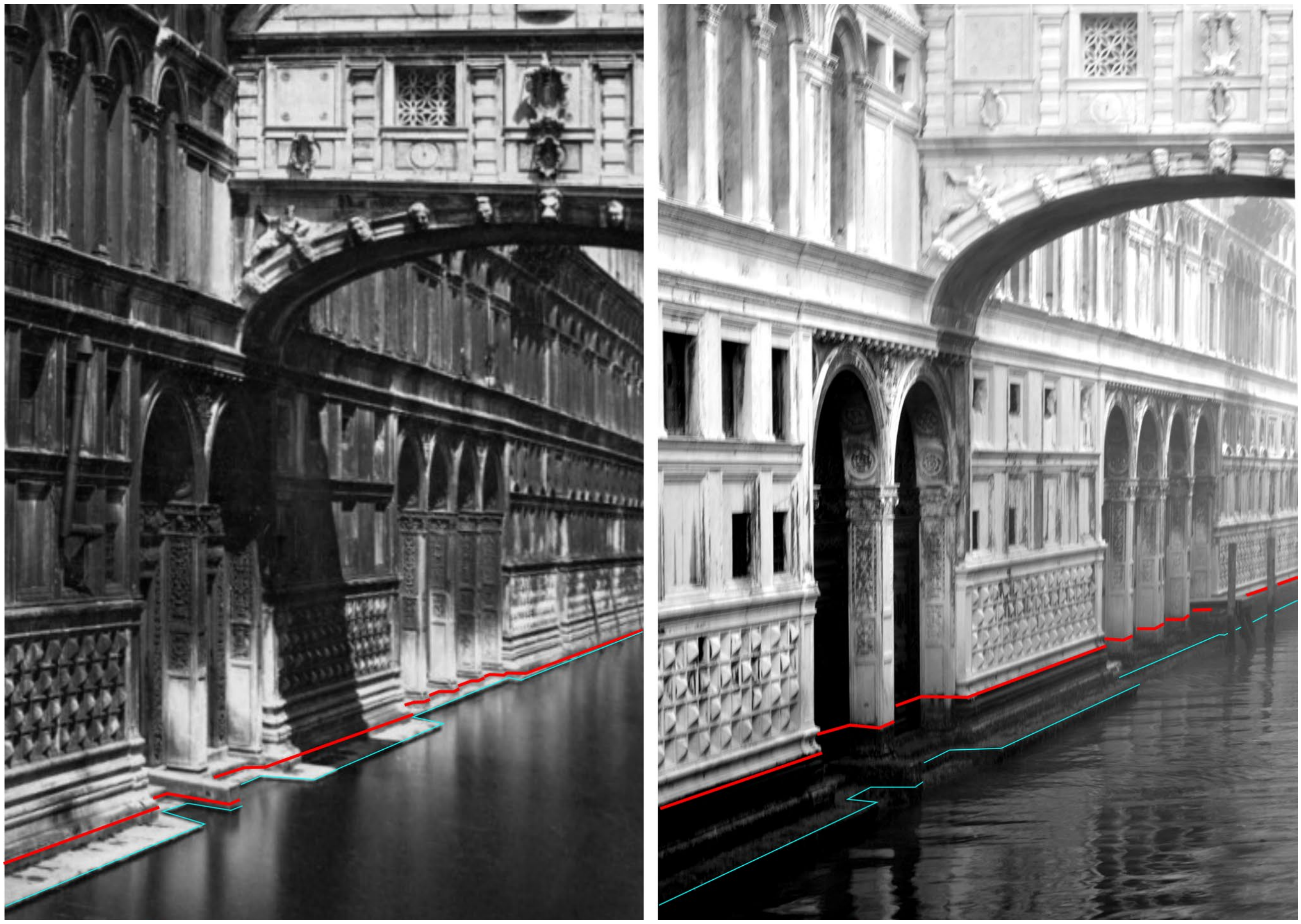


Fig. 5 Photographic comparison showing the relative sea-level rise along the façade of the *Palazzo Ducale* facing the *Rio della Canonica*. The picture on the left was taken in 1880, the one on the right after 135 years, in 2015. The *Comun marin* at the end of the 19th century was well below the base of the doors while now it has reached that level. The blue line indicates the base of the lower step and the red line indicates the *Comun marin*. Left C. Naya, 1880 (from Wikimedia Commons, image in the public domain), right I. Guarneri 2015

knots, abnormal colors and the presence of biotic degradation. The test species (in brackets the code used in the text) were (a) European softwoods: Scots Pine (*Pinus sylvestris* L.) (PIN), Larch (*Larix decidua* Mill.) (LAR) and Cypress (*Cupressus sempervirens* L.) (CIP), (b) European hardwood: Oak (*Quercus sp*.) (ROV) and (c) exotic hardwoods: Azobe (*Lophira alata* Banks ex Gaertn) (AZO), Okan (*Cylicodiscus gabunensis* Taub.) (OKA) and Bilinga (*Nauclea diderrichii* Merrill) (BIL). A set of Scots Pine panels impregnated with colloidal silica and boric acid (SIP) was also tested as they have proved to be efficient in other situations (Palanti and Feci 2013). Poplar (*Populus nigra* L.) (PIO) was also added was also added as a less durable European hardwood species to corroborate reference comparison to corroborate reference comparison.

An experimental installation (Fig. 7) was set up on one of the *Palazzo Ducale* doorways. Two identical sets of specimens were arranged in two parallel horizontal rows and positioned at the foot of the door in order to be exposed to the same environmental conditions (immersion/submersion cycles, splashing, solar radiation, temperature changes etc.) in which the real doors operate. For this purpose, some characteristic tidal levels were calculated. Mean sea level (MSL) is 32.3 cm above the Venice Datum (*Punta della Salute*, 1872). Mean high-water level (MHW) is 29.7 cm above mean sea level (62.0 cm on Venice Datum), whereas mean high-water level of neap tides (MHWN) was 12.4 cm on MSL (44.7 cm on Venice Datum). The first row was placed approximately between MSL and MHWN, whereas the second row was placed between MHWN and MHW. Three replicates for each wood species were randomly placed in each row, with the following resulting order: ROV, AZO, OKA, PIO and SIP on one rack to the left, and CIP, BIN, PIN and LAR on a second rack to the right.

Specimens were deployed on June 14, 2011. On November 15 of the same year, the samples were collected and taken to the ISMAR laboratory, where they were cleaned from fouling, which was preserved and stored for further studies. Then, each side of the panels was scanned (CanoScan LiDE 25 at 800 dpi) to obtain digital high-resolution images. The panels were stored in 70% ethyl alcohol. X-ray images were obtained at the IVALSA lab by a Radiolight apparatus (Gilardoni S.p.A., Milan, Italy), setting the current intensity at 3 mA and voltage 50–55 kV, exposing a high definition KODAK M100 Film for 3 m. Woodborers were carefully removed from the specimens and identified to the level of species. The extent of wood erosion caused by gribbles was evaluated on scanned pictures of panel surfaces through image analysis, whereas the damage produced by shipworms was assessed through X-ray photography. Tunnels were measured through image analysis of the X-ray film both as surface area covered by the tunnels (ACT) (Palanti et al. 2015) and as estimated bioeroded volume (EBV, Guarneri et al. submitted) using the free and open source software ImageJ (Schneider et al. 2012) and Inkscape (Harrington et al. 2004).

The ACT, EBV, and surface area covered by gribble galleries were used as a measure of bioerosion. The susceptibility to woodborer attack was expressed in relative terms as the ratio between the test specimens bioerosion and the one measured in Scots Pine specimens (Relative Bioerosion Ratio, RBR).

The main hydrological variables such as temperature, salinity, pH and DO, were measured using a Hydrolab Datasonde 4 multiparameter water quality logging system (Hydrolab Co., USA) from June 14 to August 12, 2011.

Results

The lower row specimens suffered intense attack (between MSL and MHWN) whereas those on the upper row (between MHWN and MHW) a few shipworms and no gribble galleries were recorded. The discussion of results is, therefore, focused on the lower row. Table 1 summarizes the main results of the experiment.

No woodborers were found on tropical woods. The only gribble present was *Limnoria tripunctata* and it was found on all the European species. The collected shipworms belonged mostly to *Lyrodus pedicellatus* and *Teredo bartschi* together with some individuals of *T. navalis*. The species compositions on the Larch panels located in the lower row were 58% *T. bartschi*, 40% *Lyrodus pedicellatus* and 2% *Teredo navalis* (average of three test specimens, 30 individuals randomly collected on each specimen). In the upper row, there were only a few small *T. bartschi*.

In the Scots Pine the density of shipworms was the highest, followed by Poplar with very close values. Larch and Cypress hosted lower but similar numbers of shipworms followed by the Oak. The Scots Pine treated with boron silicate was a little less attacked than Oak (Table 1, Fig. 8).

Shipworms were measured from X-ray images of all wood types ($n = 160$ throughout the dimensional range). The diameter of shipworm shells ranges from 0.17 to 6.31 mm. Only a small number of individuals measured more than 5 mm. The shell-size cumulative distributions for each wood species are plotted as grading curves (Fig. 9). The size distribution of the animals was similar in all types of wood except for the Poplar, which housed smaller organisms. In the Larch, the proportion of small-sized shipworms was slightly higher than the one present in the other wood species. The Cypress showed the lowest number of small bivalves.

No evident relationship between animal density and shell size has been observed. An overall exponential relationship between maximum tunnel diameter and tunnel length was observed ($y = 1.5\ x^{2.27}$, $R^2 = 0.84$, Fig. 10). These tunnel dimensions reflect the shell width and length of the living animal.

Evaluation of the woodborers' attack

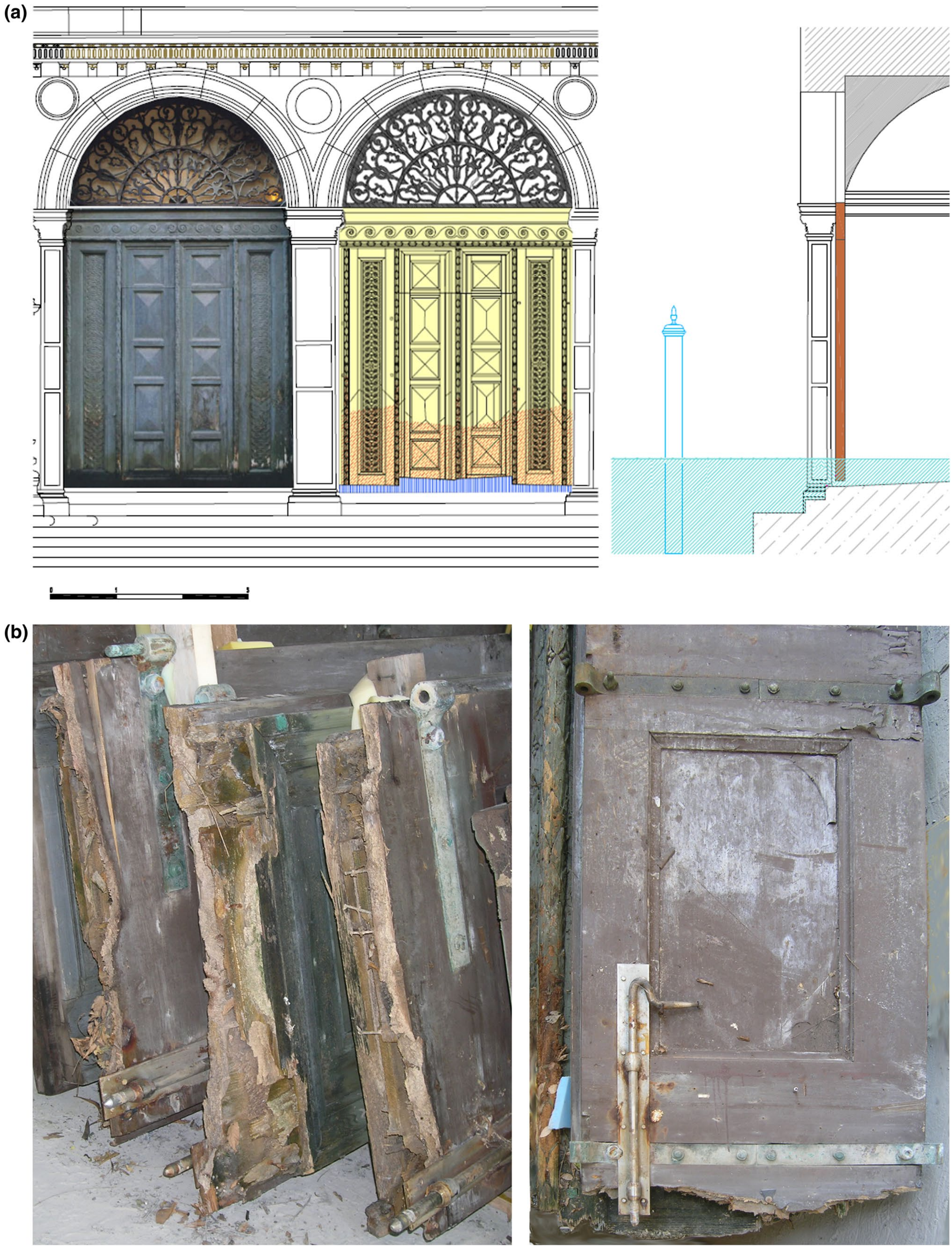
Figures 11 and 12 depict the results reported in Table 1. The largest number of gribble tunnels was recorded on the reference species and on the Larch. On the Poplar, galleries were found only on the narrow lateral sides of the panel oriented towards the building, sheltered from waves and sunlight. Few galleries were found on the Cypress and on the Scots Pine treated with boron silicate.

Pinus sylvestris appeared the most susceptible wood, bored by a large number of shipworms belonging to all the dimensional classes, whereas the Poplar, the second in order of severity, was attacked by many small shipworms. Larch and Cypress were also heavily infested. Scots Pine treated with boron silicate and Oak were the more resistant. The variability of the attack among the three replicates was particularly high in Scots Pine.

The graph of Fig. 12 shows the shipworms' Estimated Bioeroded Volume depicting the same situation. A linear relationship between the number of shipworms and the bioeroded volume was also detected (Fig. 13).

Erosion was more pronounced on the lower part of the test specimens. Shipworms entered the wood from the underside and rose vertically along the grain. Settlement also occurred through the broader faces but to a lesser extent. Few larvae entered the wood through the central hole. The height reached by the shipworms boring the wood upward reflects their density. In Scots Pine and Poplar, shipworms bored more than three-quarters of their length, in Larch about half, and in the treated Scots Pine one-third. In the Oak the tunnels stopped at about a quarter of the panel length.

In the upper row, just a few small shipworms penetrated the Scots Pine and the other European woods. The


(a)
(b)

◂**Fig. 6** **a** Diagram of a pair of water gates; left, the state before restoration, to the right, damage mapping (striped blue = missing parts due to marine woodborers, dotted red = microbiological degradation, yellow = damaged paint), **b** Damage caused by the action of marine woodborers on the water-doors of the *Palazzo Ducale*. The part below the hinge, periodically submerged by the tides, has been completely destroyed

tiny tunnels started from the underside proceeding vertically for about 5 cm up to an elevation of about 24 cm on the MSL (+ 48 cm on Venice Datum). The Oak was untouched.

Results in Table 1 are also expressed as percent ratio to the reference species to facilitate the comparison between metrics. Scots Pine was always the most impacted species, proving to be a good reference material. The ratio to the reference species shows two groups of samples: Cypress and Larch with high ratios (50 and 60%, respectively, as ACT and 50 and 70% as EBV), and Oak and treated Pine with lower values (30% for both ACT and EBV).

Scots Pine suffered the most severe damage from *Limnoria* (7.23%). Larch, the second vulnerable species, scored one-third of the reference (2.47%) followed by Poplar (0.96%). Cypress was attacked by gribbles as little as Oak (0.11% and 0.10%) and less than boron-silicate treated Pine (0.15%).

The analysis of wood-boring activity, classified according to EN 275, is shown in Fig. 14. The reference species suffered a "severe attack" with two out of three specimens in class 4 and tunnels covering over 50% of the X-ray image. The Poplar also scored class 4 (one out of three specimens), with lower tunnel coverage. The other European softwood species, Larch and Cypress, were in class 3 and 2. The Oak was the most resistant among European species, with two panels in class 2 (i.e., "moderate attack", tunnels covering not more than 25%) and one in class 1 (i.e., "slight attack", single or a few scattered tunnels covering not more than 15%). The Scots Pine treated with the experimental preservative showed a response comparable to the Oak (class 2 and 1). Tropical species had no signs of shipworms attack at all (class 0).

The gribbles boring activity was generally negligible, only the Larch and the Scots Pine exceeding 1% (avg 7.2% and 2.5%, respectively). All the species tested are in class 1 having less than 10% of the total surface covered by galleries.

Following the EN 275 overall ratings (shipworms + gribbles), the Scots Pine, Larch, Cypress and Poplar "Failed" the test, whereas Oak and treated Scots Pine were classified as severely attacked (Table 1). All exotic hardwoods have been classified as class 0 ("No attack").

Hydrological variables

Rio de la Canonica, the canal where the test was performed, is adjacent to the *San Marco* Basin, the ancient port of Venice connected to the Adriatic Sea by a deep channel. The canal receives clean seawater during flood tides but it is influenced by polluted urban waters during the ebb tide. Therefore, the hydrological parameters fluctuated according to the tidal cycle: temperature (avg 25.0, min 21.0, max 28.3 °C), salinity (avg 30.9, min 21.5, max 35.6 ‰) and pH (avg 8.1, min 7.7, max 8.4). The canal carries a high load of suspended solids and urban waste and dissolved oxygen proved to be very low (avg 2.7 ppm and 38.9% saturation, min 2.9 ppm and 0.2% sat, max 6.8 ppm and 96.0% sat). The test specimens were, anyway, deployed above mean sea level, being exposed to the air twice a day by the tide.

Discussion and conclusions

Although the use of wood in maritime structures has strongly reduced over the last century, wood-boring invertebrates are still a problem. Over time, many solutions have been proposed, ranging from coating the wood surface with sheaths and paints to replacing the wood with other materials, such as concrete or synthetic polymers including wood–plastic composites. During the 20th century a common method, very effective against shipworms but less against gribbles, has been vacuum-pressure impregnation with chromated copper arsenate (CCA) and creosote, separately or in combined action (Tupper et al. 2000). These preservatives have proved to be very harmful, especially for non-target species, and have been able to propagate throughout the food web, leading to their ban (Weis and Weis 1993; Brown and Eaton 2001; IPCS 2001; ATSDR 2005; Directive 76/769/EEC (EEC 1976); Regulation (EC) No 1907/2006 (REACH, EC 2006)). In the recent decades, less toxic impregnating agents, such as boron silicate, have been used. Recent work concerning the application of inorganic salts on tropical species (Tarakanadha et al. 2006) showed that wood treated with high retentions of ammoniacal copper zinc arsenate (ACZA) provided effective protection, better than CCA. Pholads tended to be the dominant organisms on ACZA and CCA-treated wood whereas teredinids were more prevalent on ammoniacal copper citrate (CC) or ammoniacal copper quaternary (ACQ) treatments. Another chemical modification to increase the resistance of wood against marine borers has been acetylation (Larsson Brelid et al. 2000). In the Mediterranean, a still-ongoing test on acetylated wood has given good results after the first 2 years (Palanti et al. 2017). It has also been shown that silicic acid in combination with boric acid applied to wood with vacuum pressure impregnation is effective against the decay caused by fungi

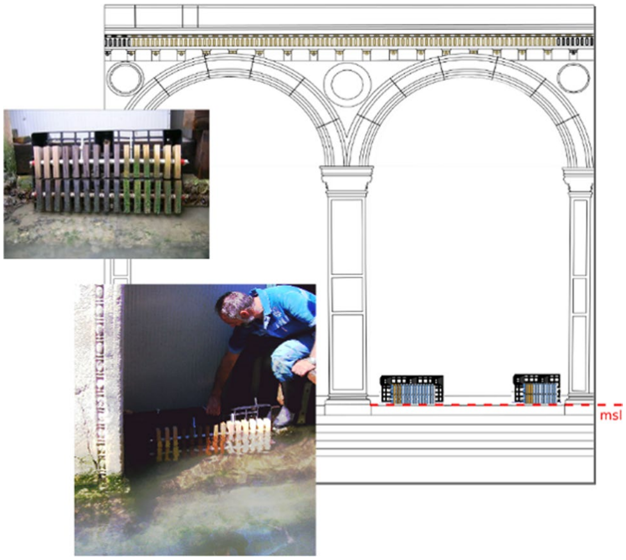


Fig. 7 Installation of the racks. The picture at the bottom shows the moment of the deployment, the picture above shows the specimens after some months of exposure

and termites (Yamaguchi 2005). This technique was already successfully applied to tests in the ground (Palanti and Feci 2013) and was therefore tried in this current study. Naturally durable wood species, mainly of tropical origin, were also widely used as substitutes for temperate, less-durable ones (Scheffer and Morrell 1998).

The maintenance and restoration of the cultural heritage require the adoption of effective, low-impact and reversible techniques. The choice is challenging in the marine environment, particularly when dealing with vulnerable architectural features such as the Venetian water-doors. In this context, the role of scientific research is to provide evidence to art and building conservators for the selection of suitable materials and techniques.

The modified EN 275 protocol proposed in this study has proved to be effective in the evaluation of the natural vulnerability of wood species in the special Venetian environment. In environments where the aggressiveness of the organisms is very high, brief exposure is more profitable than the long-term ones required by EN 275. In addition, as far as wood artifacts are concerned the location of the test should be as similar as possible to the one where the structures are designed to work. The relative bioerosion ratio, scaling the bioerosion of test specimens to the reference, allows a comparison of the results with those obtained under different experimental conditions.

The performance of both European species and alternative tropical ones was assessed. Oak and Larch were the woods historically used in the construction of water-doors and maritime structures in Venice and were, therefore, the first-choice species for the test. The Cypress is another native softwood used for ships and maritime structures in the past (Dogu et al. 2011; Liphschitz 2015), although used less frequently than Oak and Larch, and it was considered a good candidate for its durability and therefore included in the test.

Besides the softwood species used as reference (Scots Pine), a hardwood species very vulnerable to woodborers, the Poplar, was also used for comparison. The naturally durable species proposed were Bilinga and Azobe, respectively referred to as durable and moderately durable by the EN 350-2 (European Committee for Standardization 1994a, b) standard. Okan was added to the list since it is often used in marine environment as an alternative to Azobe (Gérard et al. 2017). All these tropical species can be found on the market with FSC certification (Forest Stewardship Council, https://ic.fsc.org), an international certification system that guarantees the source to be from sustainable forests with respect to the environmental, social and economic point of view.

The environmental conditions of the nearby waterway, *Rio della Canonica*, fostered a massive woodborer attack, especially by shipworms, producing significant damage over just one summer. All the European species have proved to be highly susceptible, whereas the tropical species have shown high resistance to attack. The study highlighted the vulnerability of the European wood species, confirming their relative resistance: Oak > conifers > Poplar. Scots Pine, Larch, and Poplar were the most attacked by gribbles (*Limnoria tripunctata*). The attack, although modest, occurred on the shaded sides of the panels and on the lower row suggesting that *L. tripunctata* prefer sheltered, sciaphilic habitats.

The bivalve assemblage was dominated by *Lyrodus pedicellatus* and *Teredo bartschi*. The latter is a non-indigenous species found in the Venice lagoon for the first time about 10 years ago and responsible for massive infestation of wooden dolphins and mooring piles. This species is rapidly expanding in the rest of the Mediterranean (Borges et al. 2014), giving rise to serious concerns for the future.

The boron silicate treatment on *Pinus sylvestris* performed quite well, giving it a resistance comparable to the Oak; nevertheless it was not completely effective against shipworms, which bored upward in these samples more than in the Oak. This could be due to the difference in density of the grain rings. A high silica content in wood has been acknowledged as a natural durability factor (Southwell and Bultman 1971; Trong 1988). During abrasion, the silica particles blunt the mandibles of the crustaceans and the denticulate ridges of shipworms shells. However, attempts to mimic this process through impregnation with silicon compounds have generally been unsuccessful (Cookson et al. 2007). Scown et al. (2001) showed that there was a potential for the control of teredinids using a treatment based on TEOS (tetraethylorthosilicate). Nonetheless, some doubt has been expressed on the role of silica in resisting teredinid attacks.

Table 1 Number of shipworm, shell size, and extent of the woodborers attack as assessed by image analysis

	Replicate	Shipworms								Gribbles		EN275		
		Number of shipworm per speci-men	Abundance relative to reference	Mean shell diameter [mm]	Standard deviation	Estimated bioeroded volume (EBV) [%]	Relative bioerosion ratio	Area covered by tunnels (ACT) [%]	Relative bioerosion ratio	Surface eroded by gribbles [%]	Relative bioerosion ratio	EN275 rating shipworms	EN275 rating gribbles	Overall rat-ings
Scots pine	1	164		1.8	0.5	4.3		36		7.85		3	1	Failed
	2	225		1.9	0.5	7.4		59		8.00		4	1	Failed
	3	178		1.9	0.6	8.6		64		5.84		4	1	Failed
	Mean	**189**	**1.00**	**1.9**	**0.5**	**6.8**	**1.00**	**53**	**1.00**	**7.23**	**1.00**	**4**	**1**	**Failed**
Larch	1	86		2.1	0.6	5.1		35		1.34		3	1	Failed
	2	112		1.8	0.6	5.1		37		1.80		3	1	Failed
	3	99		1.7	0.6	3.0		23		4.26		2	1	Severe
	Mean	**99**	**0.52**	**1.9**	**0.6**	**4.4**	**0.65**	**32**	**0.60**	**2.47**	**0.34**	**3**	**1**	**Failed**
Cypress	1	82		2.0	0.4	2.2		18		0.21		2	1	Severe
	2	111		2.0	0.4	2.6		23		0.02		2	1	Severe
	3	130		2.2	0.4	4.3		37		0.09		3	1	Failed
	Mean	**108**	**0.57**	**2.1**	**0.4**	**3.1**	**0.45**	**26**	**0.49**	**0.11**	**0.02**	**2**	**1**	**Severe**
Poplar	1	154		1.9	0.5	5.1		39		1.41		3	1	Failed
	2	186		2.1	0.4	6.0		47		0.42		3	1	Failed
	3	200		2.1	0.4	6.4		52		1.04		4	1	Failed
	Mean	**180**	**0.95**	**2.0**	**0.4**	**5.9**	**0.86**	**46**	**0.87**	**0.96**	**0.13**	**3**	**1**	**Failed**
Oak	1	62		1.8	0.3	1.2		10		0.11		1	1	Moderate
	2	91		1.9	0.4	2.4		20		0.07		2	1	Severe
	3	109		1.9	0.4	2.7		22		0.13		2	1	Severe
	Mean	**87**	**0.46**	**1.9**	**0.4**	**2.1**	**0.31**	**17**	**0.33**	**0.10**	**0.01**	**2**	**1**	**Severe**
Treated S. pine	1	94		1.8	0.5	2.4		19		0.27		2	1	Severe
	2	57		1.8	0.5	1.5		12		0.18		1	1	Moderate
	3	68		1.9	0.4	1.9		16		0.01		2	1	Severe
	Mean	**73**	**0.394**	**1.8**	**0.5**	**1.9**	**0.29**	**16**	**0.30**	**0.15**	**0.02**	**2**	**1**	**Severe**

The degradation classes according to EN 275 are also reported. The unaffected exotic wood panels are not included

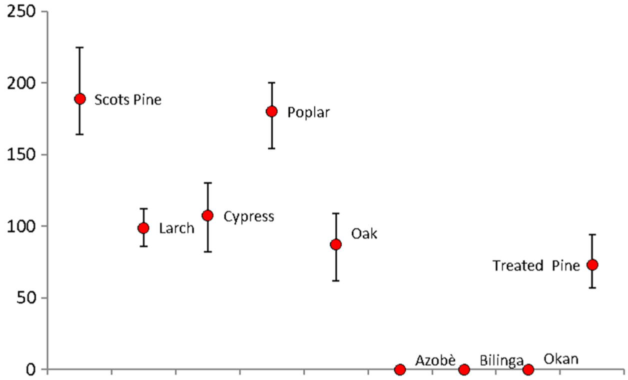


Fig. 8 Average number of shipworms present in the specimens. The vertical bars indicate minima and maxima

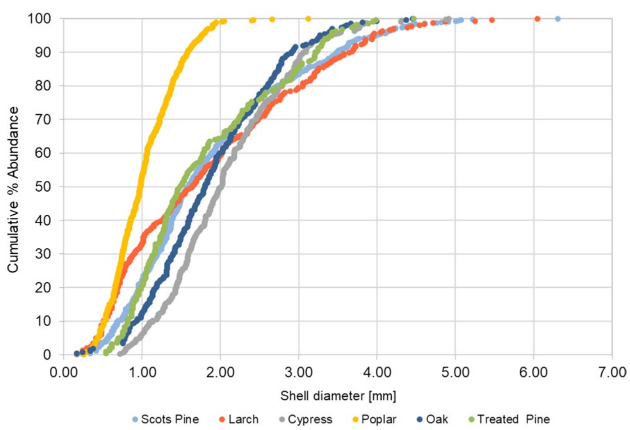


Fig. 9 Shell-size grading curves. The percentage abundances refer to the three replicates pooled

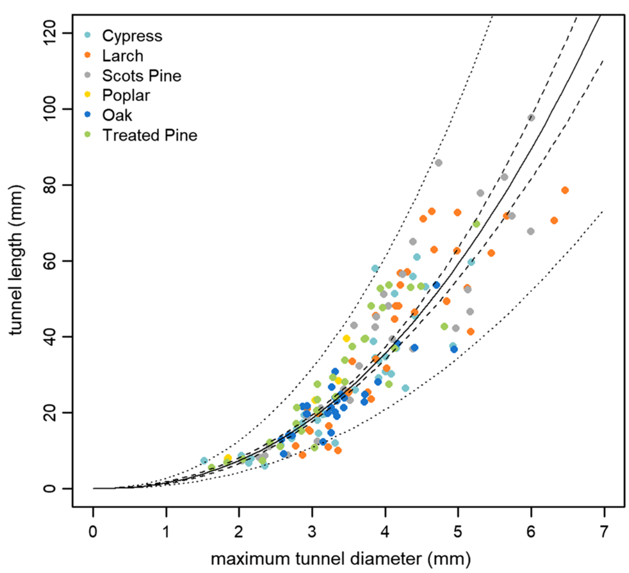


Fig. 10 Relationship between maximum tunnel diameter and tunnel length. Dashed lines indicate 0.95 confidence interval and dotted lines indicate 0.95 prediction interval

De Silva and Hillis (1980) reported that the durability of sapwood of marine durable species is lower than that of heartwood containing a similar amount of silica, arguing that silica is not the major factor for resistance.

During the present experiment, the attack decreased moving upward from mean sea level in accordance with the submergence/emergence time. The European wood specimens placed on the upper row were also damaged, although to a lesser extent, with the exception of the Oak that remained intact. These panels were less eroded in their upper parts, frequently emerging. Submergence/emergence times are a crucial factor since they affect both the wood moisture and the animal access to water, essential for respiration, planktic feeding and excretion of catabolites.

The inspection of the old doors has highlighted a physical limit to the massive attack of the woodborers. This limit is placed about 15 cm from the height of the lower hinge (Fig. 6), approximately at the highest level reached by the woodborers in the test panels.

The estimated bioeroded volume technique allowed a more precise assessment of the bioerosion than the EN 275 protocol. In addition, the "squeezing" into classes required by the EN 275 actually flattens the classification, often leading to negative judgments. The estimated bioeroded volume gives much lower values in terms of percentage, providing useful indications on structural integrity. For example, in the Poplar, an erosion of about 50% calculated from 2D projections of the tunnels on the X-ray images corresponds to an estimated bioeroded volume of less than 6%. The two values gave different perceptions of the real damage and of the consequent loss of functionality. A 6% bioerosion in terms of volume should not significantly affect the mechanical properties of the artifact, contrasting with the "failed" judgment given by EN 275 protocol. Nevertheless, the two methods gave the same ranking.

The relative sea-level rise exposed the wooden doors to the tide and consequently to physical and biological deterioration, absent at the moment of their first installation. The use of new techniques and materials for restoration is therefore justified. Under these new circumstances, it was necessary to restore the lower rails and find a technical solution to allow easy maintenance of the intertidal parts without disassembling the heavy doors.

The experimental evidence suggests that the bottom rails of the new doors should be separated from the upper part to avoid the effects of capillarity, at least up to 40 cm above mean sea level. The separation could be made either by interposing a waterproof material or by a cut. The chosen solution was to build the new bottom rails, keeping them physically separate from the rest of the gate by a cut just below the lower hinge. This strategy made possible a higher frequency of maintenance, keeping the cost low. Aesthetically, the line of discontinuity

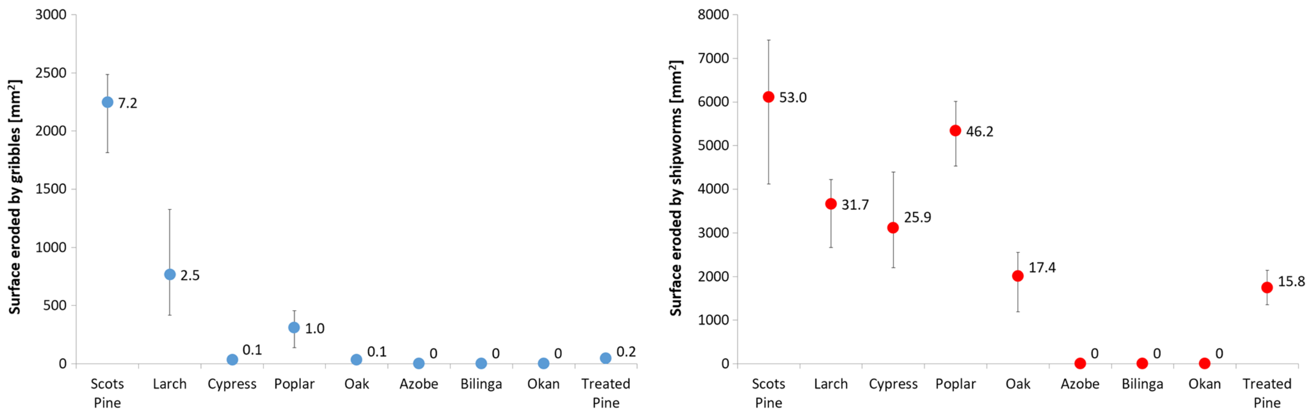


Fig. 11 Woodborers' bioerosion as detected by image analysis (mean, minima, and maxima). On the left, surface eroded by gribbles. On the right, the shipworm tunnel areas projected on the X-ray film. The number next to the symbol gives the mean percentage of bioerosion. On the *x*-axis the wood species

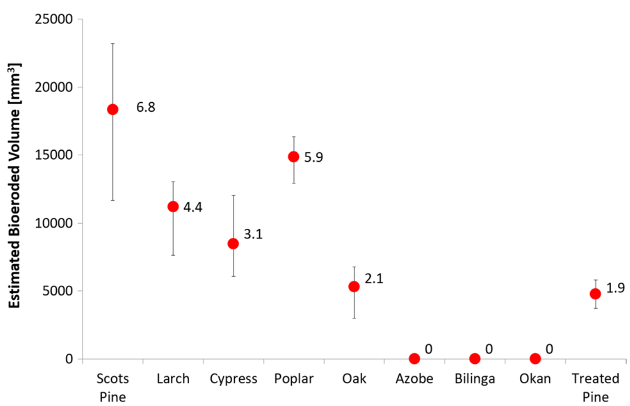


Fig. 12 Estimated bioeroded volume, mean, and extreme values. The number next to the symbol gives the mean percentage of bioerosion

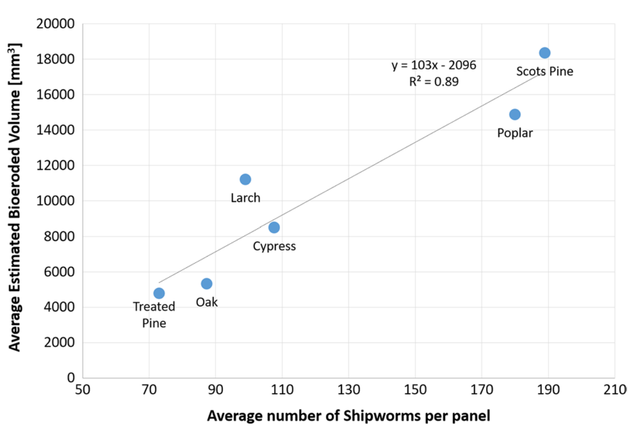


Fig. 13 Relationships between the estimated bioeroded volume and number of shipworms (average of the three test specimens)

between the new self-standing bottom rails and the original upper portions was only slightly noticeable from the outside. Doors were finally coated with marine-grade paint (Fig. 15).

At the moment of the restoration of the first two gates, in September 2013, the strategy of the local Superintendence was to follow the philological approach by excluding the use of non-local wood. Therefore, although the results suggested the use of exotic, durable wood, Larch was chosen to build the bottom rails of the first pair of doors. After 2 years (2015), the bottom rails were removed for periodic maintenance and appeared in good condition. Two more years later (2017), during a second maintenance, the Larch bottom rails exhibited a massive attack by marine woodborers and almost completely failed. Following a revised conservative approach, it was decided to change the restoration strategy by experimenting on a second pair of gates with the use of resistant tropical species for new bottom rails. This pair of doors, installed in June 2015, was thus built with a core of Azobe and the external carved panels in Larch. In line with the prediction of the field experiment, these doors have been attacked only on the Larch panels, keeping their structural integrity. Recognizing the efficacy of the new solution, in 2017 the first two doors were once again restored using this multi-layer technique consisting in an inner plank in Bilinga followed by a stainless steel sheet, and finished by the outer panel partially rebuilt in Bilinga. The use of Bilinga was justified since it has proven to be resistant to woodborers and at the same time to be easier to carve than Azobe with ordinary carpentry machines. At the beginning of 2018 the Bilinga bottom rails were checked and showed a mechanical dysfunction due to swelling. The swelling was not very evident in the small test specimens used during the field test,

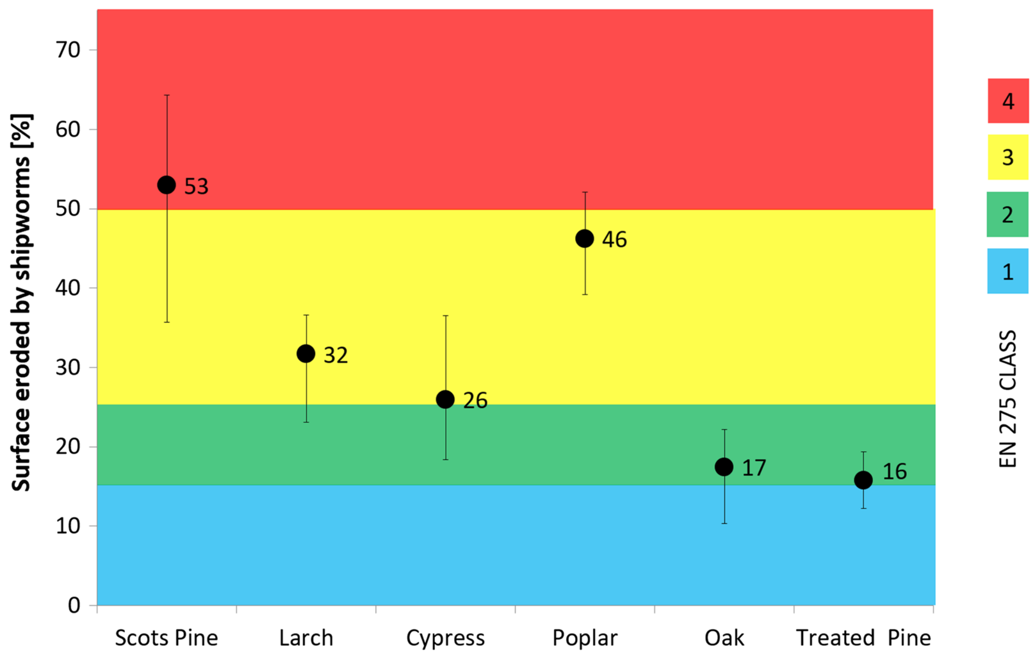


Fig. 14 Ratings of shipworm attack according to EN 275

Fig. 15 The water-doors after restoration. The image from the inside shows the separation between the upper and lower parts, facilitating maintenance work

suggesting the deployment of prototype artifacts, in addition to test panels, in a future phase of experimentation.

This work demonstrates how the wooden cultural heritage is subject to a particular degradation as a consequence of climate change, especially in the marine environment. The key to successful restoration of maritime wooden cultural heritage can only benefit from the integration of the different restoration approaches with the results obtained from on-site experimentation.

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