Research Article

*Mediterranean Marine Science*
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
www.hcmr.gr
DOI: https://doi.org/10.12681/mms.39039

# Damage and economic impact of wood-borers (Bivalvia, Teredinidae) on artisanal fishing in Morocco: a case study

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Contributing Editor: Argyro ZENETOS

Received: 01 October 2024; Accepted: 12 December 2024; Published online: 06 February 2025

## Abstract

This study presents the first comprehensive assessment of the economic impact of wood-boring bivalves from the family Teredinidae on artisanal fishing in Tangier, Morocco, following the establishment of a new fishing port that has seen a marked increase in infestations since its opening in 2018. We conducted a questionnaire survey with over 40 artisanal shipowners to evaluate the extent of damage and repair costs associated with teredinids. The results indicated that 77.5% of the fleet was affected, with a significant proportion reporting moderate damage. Analysis of wood samples revealed two dominant teredinid species: *Lyrodus* cf. *pedicellatus,* and *Teredo bartschi*, both recorded for the first time in Morocco, marking them as alien invasive species in the region. The vulnerability of wooden boats, particularly those constructed from softwoods (e.g., *Picea* sp. and *Pinus* sp.), was evident, while polyester boats remained unaffected. Annual repair costs due to shipworm damage were estimated to exceed Moroccan Dirham (MAD) 4.7 million (US$ 470,000), representing over 6% of the artisanal fishery annual value, significantly impacting the livelihoods of artisanal fishermen. Shipping activities through the Strait of Gibraltar likely facilitated the introduction of teredinids. Their adaptability and rising sea temperatures suggest teredinids' range will continue to expand, threatening local fishing infrastructure. The findings underscore the urgent need for targeted management strategies to mitigate the economic and ecological impacts of these invasive species on artisanal fishing communities.

**Keywords:** Biological invasion; economic impacts; invasive species; *Lyrodus pedicellatus;* teredinids; *Teredo bartschi;* traditional fishing.

## Introduction

Bivalve wood borers of the family Teredinidae (teredinids), commonly known as shipworms, exhibit a distinct body pattern that distinguishes them from other bivalves. Their worm-like appearance, characterized by an extremely elongate body and greatly reduced shells, initially led Linnaeus to misclassify them as Annelids. It was not until 1733 that Sellius correctly identified them as bivalves (Sellius, 1733). These organisms bore into wood during their larval stage, constructing shell-lined tunnels, which they seal with a pair of calcareous structures called pallets that flank their siphons (Turner, 1966). This adaptation provides protection against predation, dehydration, and environmental stress, freeing the valves from their protective function and enabling them to specialize as boring tools, equipped with minuscule rasp-like teeth (Turner, 1966).

The majority of teredinids are obligate wood borers, depending on wood for both shelter and as their primary source of nutrition (Distel, 2003). Found from cold to tropical marine environments, and even brackish waters, from the intertidal zone to 200 m, they are the primary degraders of submerged wood. By contributing to the natural biodegradation of wooden debris, they release nutrients that benefit other organisms (Cragg *et al.*, 2020). Additionally, once shipworms die, their abandoned tunnels provide habitat and shelter for various marine organisms such as small fish and crustaceans, and serve as nurseries, enhancing biodiversity in marine environments (Hendy *et al.*, 2014).

Despite their beneficial ecological role, teredinids also pose a significant threat to man-made wooden structures in marine environments. The extent of this hazard depends on the species present and environmental conditions, which can fluctuate annually. In the Mediterranean Sea, six species of Teredinidae have been reported (Borges *et al.*, 2014a; Niekerk *et al.*, 2022). Among these, *Teredo navalis* Linnaeus, 1758, has been named one of the 100 worst alien marine invasive species in the Mediterranean (Streftaris & Zenetos, 2006). However, it is not the most common species in the Mediterranean (see map in Niekerk *et al.*, 2022) and has subsequently been considered cryptogenic (Borges *et al.*, 2014a; Zenetos *et al.*, 2017, 2018). This species is also widely distributed in the Northeast Atlantic (NEA) (Borges *et al.*, 2014a). Another species, *Nototeredo norvagica* (Spengler, 1792), which was once thought to represent two different species –*Teredo norvagica* in the Atlantic and *Teredo utriculus* in the Mediterranean (Roch,1940)– has since been confirmed as a single species inhabiting both the Mediterranean and the Atlantic coasts of Europe, similarly to *Teredo bartschi* Clapp, 1923 (Borges *et al.*, 2014b).

Other species reported only in the Mediterranean include *Bankia carinata* (Gray, 1827), *Lyrodus mersinensis* Borges & Merckelbach, 2018, and *Teredothyra dominicensis* (Bartsch, 1921) (Borges *et al.*, 2014a; Shipway *et al.*, 2014; Tagliapietra *et al.*, 2021). *Lyrodus pedicellatus* (Quatrefages, 1849) has also been recorded in the Mediterranean, although its presence in this region remains uncertain due to the species' complex taxonomy. In the NEA, however, *L. pedicellatus* is the only species reported in this complex (Borges & Merckelbach, 2018) and is considered the most destructive teredinid species in southern Europe, extending as far as the British Channel (Borges *et al.*, 2014a).

Despite several studies on marine wood-borers in the Mediterranean and Atlantic (e.g., Roch, 1940; Sen *et al.*, 2010; Borges *et al.*, 2014a; Appelqvist *et al.*, 2015), records from Morocco's coasts are sparse. Searches of global databases such as the Global Invasive Species Database (GISD, 2024) and the Global Biodiversity Information Facility (GBIF, 2024) yielded only a single record of *T. navalis* in Agadir (Ardovini & Cossignani, 2004). A review of the literature added two more teredinid records in Morocco, *Teredora malleolus* (Turton, 1822) and *N. norvagica* in Tangier (Pallary, 1902). However, a recent survey of molluscs along the Moroccan coast (Irikov & Gerdzhikov, 2013) and the latest update of invasive marine species (Mghili *et al.*, 2024) did not report these or any other teredinid species.

The range and distribution of teredinids can vary unpredictably, sometimes resulting in severe damage, as seen in San Francisco Bay between 1919 and 1921 when *Teredo navalis* caused extensive destruction to ships and waterfront structures, with losses estimated in the billions of dollars (Distel, 2003). More recently, shipworms have been identified as the second most costly species in the Northeast USA, causing damage worth an estimated US$ 0.17 billion (Fantle-Lepczyk *et al.*, 2022). Globally, damage from teredinids is estimated to exceed US$1 billion annually (Distel *et al.*, 2011), with the economic toll particularly severe in underdeveloped regions where fishermen often rely on wooden boats and low-cost paint for the hull protection (Cobb, 2002).

This study highlights the emergence of shipworms in the new fishing port of Tangier, an unreported issue posing considerable environmental and socio-economic risks. Limited data on shipworm damage to fishing boats underscores the need for research to identify the teredinid species present in the new port of Tangier, estimate the extent of the damage they cause, and assess their socio-economic impact on local fishermen. The findings will provide critical information for decision-makers to mitigate the effects of these invasive species.

## Materials and Methods

### *Study area*

#### *Geographic location*

Tangier port ((35.7905° N, 5.8080° W) is situated in the Tangier-Tetouan region, near the entrance to the Strait of Gibraltar. It lies at the confluence of the Atlantic Ocean and the Mediterranean Sea, within a harbour positioned between Cape Spartel and Cape Malabata (Fig. 1). The Tangier port redevelopment project, launched in 2010 and finalized in 2018, included developing hubs for yachting, passengers, and fishing, following the transfer of commercial traffic to Tangier Med port (MEE, 2016). Official reports state that the port accommodates 513 artisanal fishing boats and canoes (MAPMDREF, 2022a). The artisanal fishery production in Tangier and its surrounding areas was valued at over US$ 7.5 million in 2022, employing around 2,200 active fishermen, all male (MAPMDREF, 2022b).

#### *Environmental conditions*

The average sea-water temperatures in Tangier vary seasonally, with 16.6°C in winter, 16.7°C in spring, 20.8°C in summer, and 19.8°C in autumn. Tangier's waters display a distinctive salinity profile, featuring a deeper, high-salinity layer (38‰) originating from the Mediterranean, overlaid by a surface layer of lower-salinity Atlantic water (36.6‰). These salinity values are subject to fluctuations based on tidal movements, with salinity typically higher during high tide than low tide (Sea water temperature, 2024).

### *Data collection*

To estimate the damage caused by teredinids in the new fishing port of Tangier, a questionnaire was distributed in June 2023 to over 40 artisanal shipowners. The questionnaire gathered detailed information on each boat, including the extent of damage in 2022 and 2023, as well as details regarding the boat's age, type, and hull material. The questionnaire was divided into two sections: one collecting general information about the boat and the other focused on assessing wood boring damage.


*Fig. 1:* Location of the Port of Tangier, 1: The new fishing port of Tangier; 2: passengers and cruise area; 3: The old fishing port of Tangier; 4: now yachting zone (Ports En Chiffres, 2016). The map represents the Strait of Gibraltar, the red dot marks the location of the Port of Tangier. (Map sourced from https://maps-for-free.com/ under GFDL license).

Additionally, discarded wood fragments from damaged boats were collected at the shipyard where biannual repairs typically occur in February and July. Since July 2023 data were not available at the time of the survey, an average from 2022 was used for comparison with February 2023 data.

### *Laboratory assessment of wooden samples*

Three wooden samples were obtained from the submerged portions of different boats undergoing repairs at the shipyard. The first sample (A) was pine wood (*Pinus* sp.), collected in early March 2024. The second sample (B) was spruce wood (*Picea* sp.), collected in late March. The third sample (C) was mahogany (*Swietenia* sp.) collected in early April.

In the laboratory, the samples were longitudinally sliced to extract the teredinids from the tunnels. The extracted specimens were preserved in 95% ethanol for identification. Identification was based on pallet morphology using Turner's key (1971) and plates from Turner (1966). The pallets were imaged under a stereomicroscope to illustrate the species present in each wooden sample.

The total number of teredinid specimens was estimated based on the complete specimens and detached pallets present in the samples. The relative abundance of each species was calculated following species identification.

### *Wood boring hazard*

To evaluate the extent of damage to artisanal fishing boats in 2022 and 2023, comparative statistical analyses were performed. These analyses focused on repairs carried out in 2022 and February 2023, as data for July 2023 were unavailable. Damage was estimated based on the number and cost of annual repairs, which were linked to the degree of damage and the number of defective wooden parts replaced. The severity of wood-boring damage was assessed using the ranking system described in *EN 275* (1992), which employs a scale of 0 to 4. A score of 0 indicates no attack, while a score of 4 represents maximum attack, leading to the complete destruction of the wood.

## Results

### *Survey data analysis*

#### *Emergence of teredinids*

The results from the survey underscore a sharp contrast between the historic port and the new fishing port of Tangier regarding the impact of shipworm damage. In the old port, teredinid damage was virtually non-existent, with minimal deterioration reported: No deterioration was observed for 85% of the boats, while the remaining 15% only reported a slight deterioration. However, after the opening of the new fishing port in June 2018, the problem increased dramatically. This significant shift highlights the vulnerability of the newly constructed port, where marine wood borers have quickly become a pressing issue for most of the artisanal fleet.

A large majority (74%) of shipowners reported that shipworm damage reappeared within six months of each repair, with only polyester boats remaining untouched. Wooden boats, especially those made of *Picea* sp. (white wood) and *Pinus* sp. (red wood), were particularly vulnerable to extensive damage to their submerged areas (Fig. 2A and B), evidenced by numerous calcareous-lined tunnels typical of shipworms (Fig. 2C and D).

*Fleet composition and vulnerability*

The fleet is predominantly composed of artisanal boats (77.5%), which are small wooden vessels, typically 5 to 6 meters in length and with a tonnage of less than 2 gross tons (GT). These boats are equipped with outboard motors and are used exclusively in fresh fishing (MAP-MDREF, 2024). The remaining 22.5% are canoes which are even smaller in size (Fig. 3a) –therefore, in this study, the term "boat" is used to refer to both types. Notably, all wooden boats, regardless of type, were affected by shipworm activity. The distribution of hull materials among the fleet reveals a heavy reliance on vulnerable wooden constructions, with "white" wood (*Picea* sp.) comprising 50% of the fleet, followed by "red" wood (*Pinus* sp.) at 30%. Only a small percentage of boats utilized polyester or mahogany (*Swietenia* sp.) hulls (5% each), while mixed hull materials–a combination of wood and polyester–accounted for 10% (Fig. 3b).

*Damage and repair costs*

The financial burden of shipworm damage is substantial. Forty-five percent of the fleet experienced moderate damage in 2022, with a similar rate observed in 2023 (Fig. 4). The repairs were categorized based on severity using EN 275 (1992) scale, with most boats experiencing moderate (level 2) damage. However, some cases of severe damage (levels 3 and 4) required major repairs,


***Fig. 2:*** Teredinid damage to artisanal fishing boats; a- Damaged boats queueing at the shipyard, 2023; b- The magnitude of damage observed on boat hulls; c- Teredinids in a damaged wooden piece from a boat in the new fishing port of Tangier, 2023. d- Shipworm tunnels in the wooden hull of a boat showing the typical calcareous lining (arrows).

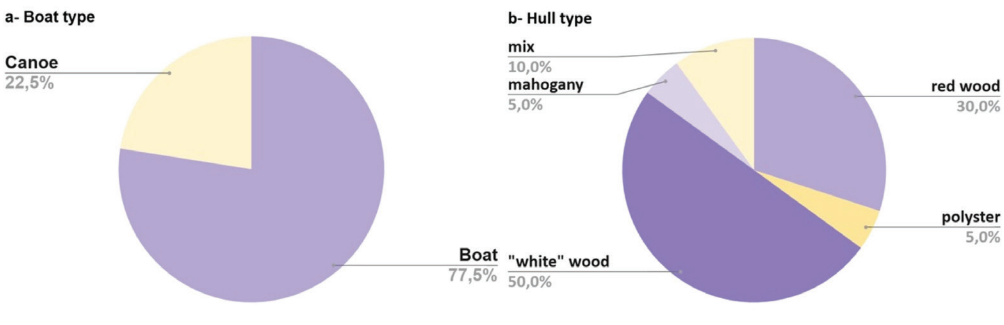


***Fig. 3:*** Distribution of fishing vessels by a- type (boats and canoes), and b- hull materials where "white" wood refers to white coloured wood, e.g., *Picea* sp.; red wood to dark coloured wood, e.g., *Pinus* sp.; and mix to a combination of wood and polyester (usually wood covered by polyester).

including the replacement of significant sections of the boat hull, which can be particularly expensive. Overall, there was no significant difference between the two years, only a slightly higher percentage of repairs in 2023 (17% more than the average in 2022).

The average annual repair costs per boat were estimated at MAD 10,000 per boat (US$ 1,000). While expenses include also the cost of raising and lowering the boat into the sea with a crane, as well as the cost of mooring it at the 'Baradero' (Fig. 2A), this figure varies significantly depending on the severity of the damage. For boats requiring multiple repairs per year, or extensive work involving the replacement of major structural elements such as the keel (Fig. 2B), the costs could exceed MAD 20,000 (US$ 2,000). Furthermore, the operational disruptions caused by repairs – ranging from one week to a month – also add indirect costs through lost fishing time and income.

When these costs are extrapolated across the entire fleet of 513 artisanal boats ( MAPMDREF, 2022a), the annual economic damage exceeds MAD 4,7 million per year (US$ 470,000) (Table 1). Moderate damage accounts for the bulk of this cost (59%), with an estimated total of MAD 2,8 million (over US$ 280,000), and high damage accounts for 24% of the costs, with an estimated total of MAD 1,14 million (over US$ 114,000). But even the smaller fraction of boats with severe damage (10%) incurs significant financial strain [MAD 455,000 (over US$ 45,500)] (Fig. 5). These high repair costs are compounded by the lack of insurance coverage and the reliance on traditional carpenters for repairs, whose work, while cheaper (MAD 10,000 to 20,000) than that of specialized companies (MAD 40,000 to 50,000), still represents a substantial financial burden for artisanal fishers. Additionally, the loss of fishing time while boats are undergoing repairs leads to indirect costs, such as lost income, further intensifying the economic strain on artisanal fishermen, despite efforts to schedule repairs during low-income months.

*Hull material and damage severity*

The severity of damage was closely linked to the type of hull material used. Polyester boats showed no damage, while wooden boats and those with mixed materials (wood covered in polyester) displayed varying degrees of infestation. Boats constructed with "white" wood (e.g., *Picea* sp.) and "red" wood (e.g., *Pinus* sp.) suffered the most extensive damage. Mixed hull materials (wood and polyester) did show some moderate damage, indicating that while the polyester layer offers some protection, it is not entirely effective in preventing shipworm infestation (Fig. 5).

The persistence of damage, with 65% of boats requiring biannual repairs or more, highlights the ineffectiveness of current maintenance strategies. Traditional methods, such as painting hulls with antifouling paint or mixing biocides into the paint, have not been successful in reducing the impact of shipworm activity. The use of denser wood such as *Swietenia* sp., with a higher strength/weight ratio (Cragg *et al.*, 1999), does not confer complete protection against shipworms although hulls built on this wood showed less attack than those built on lesser dense woods such as *Pinus* sp. and *Picea* sp.

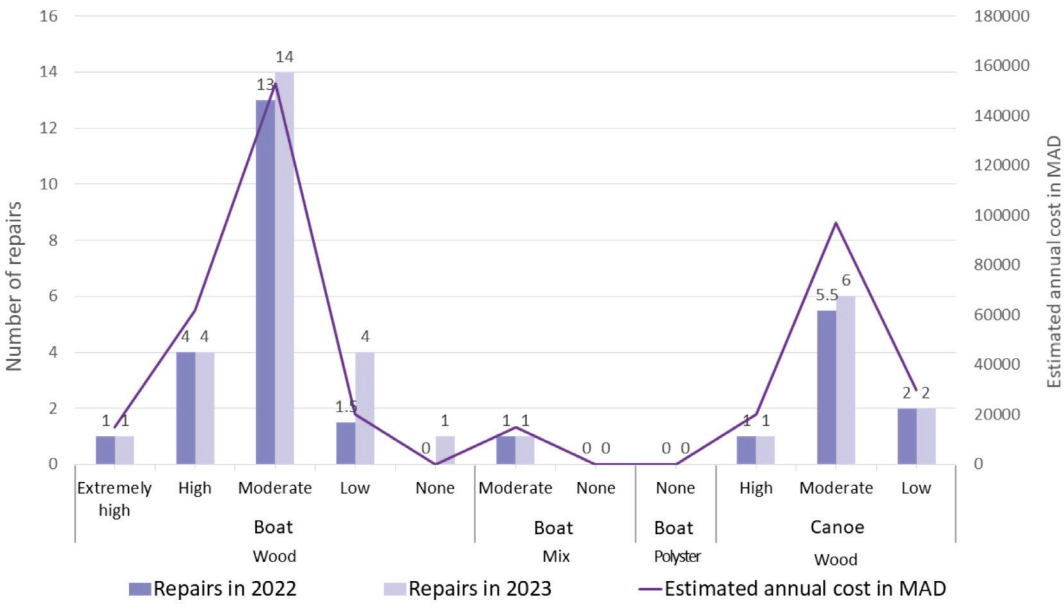


***Fig. 4:*** Comparison of repairs on 2022 and 2023 by boat type and hull material, as well as the average annual cost. Data for July 2023 were unavailable at the time of the questionnaire thus an average was used for 2022 (Repairs are usually done biannually in February and July).

**Table 1.** Estimated annual damage caused by shipworms to the artisanal fishing sector at the new fishing port of Tangier. (Damage is assessed on the scale in EN 275, (1992), low damage concerns boats under 6 months old with minor damage requiring no immediate repairs. Sample size refers to the questionnaire results (for 40 boats) while the total number of boats in the port of Tangier is 513. m: million, t: thousand.

| Type | Hull material | Sample size | Damage scale | Number of damaged boats in sample size | Total damaged boats in the port of Tangier | Average annual repair cost in MAD | Total annual cost in MAD |
|---|---|---|---|---|---|---|---|
| Boat | Wood | 25 | 0 | 4 | 51 | 0 | 0 |
| | | | 1 | 2 | 26 | 9 t | 234 t |
| | | | 2 | 13 | 167 | 10 t | 1,67 m |
| | | | 3 | 5 | 64 | 10 t | 640 t |
| | | | 4 | 1 | 13 | 15 t | 195 t |
| | Polyester | 2 | 0 | 2 | 26 | 0 | 0 |
| | Wood covered in polyester | 4 | 0 | 3 | 38 | 0 | 0 |
| | | | 2 | 1 | 13 | 15 t | 195 t |
| Canoe | Wood | 9 | 1 | 1 | 13 | 9 t | 117 t |
| | | | 2 | 5 | 64 | 15 t | 960 t |
| | | | 3 | 2 | 25 | 20 t | 500 t |
| | | | 4 | 1 | 13 | 20 t | 260 t |
| Total | | 40 | | 40 | 513 | | 4,771 m |

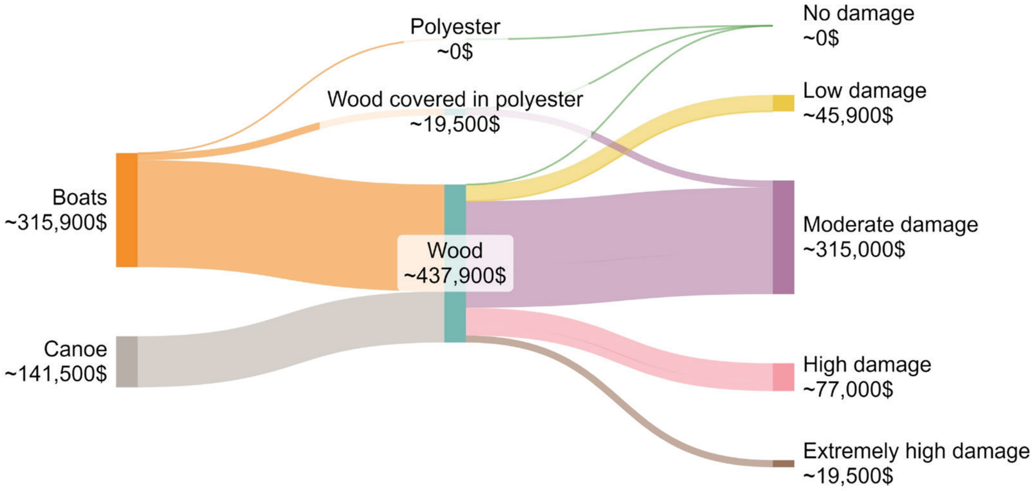


***Fig. 5:*** Distribution of estimated annual costs caused by shipworms to the artisanal fishing sector at the new fishing port of Tangier (in MAD) by type of boat, hull material and average damage.

### *Teredinids in Tangier Port*

#### *Species composition and distribution*

The laboratory analysis of wood samples from shipyard revealed two main species of teredinids: *pedicellatus-like Lyrodus* hereinafter *Lyrodus* cf. *pedicellatus* and *Teredo bartschi.* The presence of these species highlights the biological diversity of teredinids in Tangier's waters and their ability to cause widespread damage.

Among the tree wooden samples (A, B and C), *Lyrodus* cf. *pedicellatus* was the dominant species, found in all samples with varying frequencies. In samples B and C, it represented 100% of the teredinids present, while in sample A, it accounted for 69%. *T. bartschi* was found only in sample A, where it represented 25% of the teredinid population (Table 2).

#### *Pallet Morphology and variability*

Systematic account
Order Myida Stoliczka, 1870
Superfamily Pholadoidea Lamarck, 1809
Family Teredinidae Rafinesque, 1815
*Lyrodus* cf. *pedicellatus*

**Table 2.** Species of wood and wood-boring species present in the wooden samples collected from the shipyard.

| Sample | Wood species | *Lyrodus* cf. *pedicellatus* | *Teredo bartschi* | Total |
|---|---|---|---|---|
| A | *Pinus* sp. | 11 | 4 | 16 (2 pallets unidentified) |
| B | *Picea* sp. | 5 | 0 | 9 (7 pallets unidentified) |
| C | *Swietenia* sp. | 1 | 0 | 1 |

The pallets of *Lyrodus* cf. *pedicellatus* exhibited a high degree of morphological variation (Fig. 6). The calcareous portion of the blade was in most pallets an unsegmented thick piece distally conical (Fig. 6B). In some pallets, however, horizontal striation was observed on the inner side of the blade (Fig. 6D). The distal half of the blade was covered by a loose-fitted periostracum with concave to U-shaped distal margin and more or less straight-sided, sometimes extending as lateral horns. The colour of the periostracum varied widely from light brown to nearly black.

Species could not be ascertained from pallet morphology only, because the morphospecies *L. pedicellatus* is a species complex (Borges & Merckelbach, 2018).

*Teredo bartschi Clapp*, 1923

Pallets of *Teredo bartschi* Clapp displayed distinct morphological features. The calcareous portion of the blade was a single thick piece, about as wide as long, not divided distally. Distal margin covered by a golden periostracum, U-shaped extending laterally as small horns (Fig. 7).


***Fig. 6:*** Pallets of *Lyrodus* cf. *pedicellatus* extracted from the samples from the boats, showing variable morphology and colour of periostracum. A- outer and inner view, respectively of pallet B01; B- outer and inner view, respectively of pallet A16; C- outer and inner view, respectively of pallet A14; D- outer and inner view, respectively of pallet A15. scale bars= 2mm. bl= blade; st= stalk.

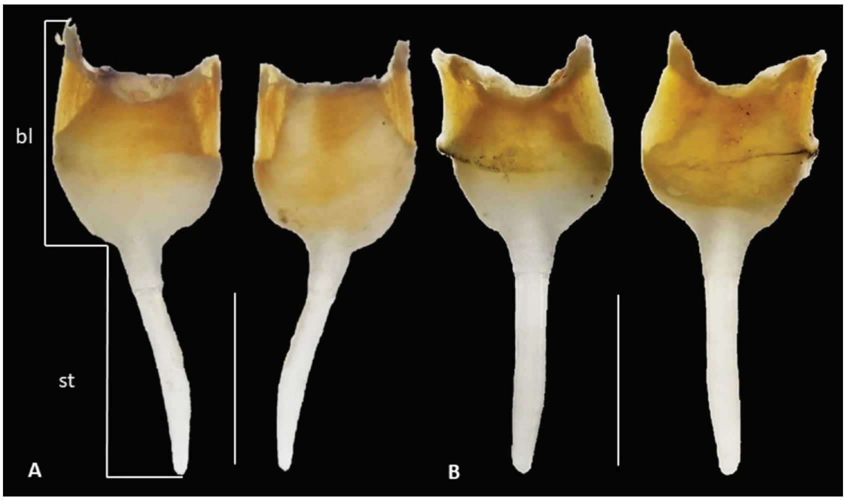


***Fig. 7:*** Pallets of *Teredo bartschi* extracted from sample A. A- outer and inner face, respectively of pallet A19; B- outer and inner face, respectively of pallet A13. Scale bars= 2mm. bl= blade; st= stalk.

## Discussion

### *Damage caused by teredinids in the new port of Tangier*

Biological invasions represent significant global economic threats, yet detailed cost assessments for many nations in the Global South, particularly in Africa, remain scarce (Diagne *et al.,* 2021), While the global economic impact of marine wood-borers is estimated to reach billions of dollars annually (Distel, 2003) –a widely cited figure despite limited recent data–local studies quantifying the specific costs of teredinid damage are especially lacking, highlighting the relevance of this research. Although research on non-indigenous species (NIS) and biological invasions occasionally addresses this damage (e.g., Fantle-Lepczyk *et al.*, 2022), teredinids are often overlooked due to their inconspicuous habitat, even in bivalve-focused surveys (e.g., Irikov & Gerdzhikov, 2013; Mghili *et al.*, 2024). This study provides the first detailed analysis of teredinid species in the new fishing port of Tangier, assessing the socio-economic risks they pose to the artisanal fishing sector.

Prior to 2018, shipworm damage in Tangiers's historic port was minimal, with only a few boats reporting slight damage (maximum 1 on the EN 275 scale). As a result, little attention was given to these organisms, and no data was available on the species responsible. Following the opening of the new fishing port in June 2018, however, teredinid damage surged, affecting 77.5% of the artisanal fleet. Most vessels (47.5%) experienced moderate damage (rated 2 on the EN 275 scale), while 10% of wooden boats remained unaffected, likely due to the use of more durable timber.

Vulnerability to shipworm damage varied across wood species, with *Pinus* sp. being the most affected (16 specimens), followed by *Picea* sp. (9 specimens) and *Swietenia* sp. (1 specimen). This aligns with the established understanding that softwoods are more susceptible to shipworm damage than hardwoods (Williams *et al.*, 2018). Polyester hulls, as expected, were immune to shipworm attacks, as these organisms do not bore into synthetic materials. However, 25% of wooden boats covered with polyester still suffered moderate damage, suggesting that the polyester barrier was not fully effective. This suggests that shipworm larvae may be able to detect chemical cues from the underlying wood, allowing them to penetrate the protective layer, though the nature of these cues remains unclear (Toth *et al.*, 2015). Similar cases have been documented, such as when *T. navalis* larvae penetrated polypropylene mesh due to their minute size (Culliney, 1975), as observed in shipwreck protection studies using geotextile sheathing (Borges, 2007).

The potential annual economic impact of invasive species in Morocco has recently been estimated at US$ 1.61 billion (unpublished data). However, this estimate does not account for the annual repair costs associated with shipworm damage. In the port of Tangier alone, annual repair costs due to shipworm damage–coinciding with the port's opening and highlighting the vulnerability created by its design–are now estimated to exceed MAD 4,7 million. This figure represents over 6% of the artisanal fisheries' annual value, which is estimated at MAD 74 million (MAPMDREF, 2022b). Indirect costs, such as the lost income during boat repairs, further exacerbate the economic burden on artisanal fishermen, threatening their livelihoods.

This increase in teredinid infestations aligns with the understanding that ports are hotspots for invasive species, with global shipping playing a key role in their spread (Seebens *et al.*, 2013). The new port of Tangier is particularly vulnerable due to its strategic location on a major shipping route between the Mediterranean and the Atlantic, as well as its proximity to Tanger Med, one of the world's largest ports, which has connections to over 180 ports in 70 countries (Salvan, 2019; Hand, 2021). While the increasing volume of ballast water discharge from larger, faster ships likely facilitates the transport and survival of marine organisms (Geburzi & McCarthy, 2018), driftwood, carried by water, also acts as a natural "raft" or "dispersal agent", promoting the spread of wood-boring invertebrates across marine environments (Thiel & Gutow, 2005). These factors are facilitating the establishment of the invasive teredinid species documented in this study.

The ongoing impact of these invasive species underscores the urgent need for continuous monitoring to track their spread. Regular assessments are essential for providing timely, accurate data for environmental managers (Zenetos *et al.*, 2017), enabling the implementation of informed policies and rapid response protocols. These measures will help mitigate the effects of invasive species, safeguarding both the region's economic stability and ecological health.

### *Teredinid species present in Tangier new port and their potential origin*

Until now, no teredinid species had been recorded as established along the coast of Tangier. Pallary (1902) reported *N. norvagica* and *T. maleollus* in driftwood from Tangier Bay, but no subsequent reports followed. This study provides the first documentation of *Lyrodus* cf. *pedicellatus* and *T. bartschi* in the new port of Tangier, establishing them as invasive species. Both species are known from the Mediterranean and Atlantic (Roch, 1940; Borges *et al.*, 2014b; Tagliapietra *et al.*, 2021), but their presence in Tangier had not been previously reported.

Among the three wooden samples analyzed, *Lyrodus* cf. *pedicellatus* was the most abundant species. This morphospecies has been observed in both the Mediterranean and the Northeast Atlantic (NEA) (Roch, 1940; Bobat, 1995; Sen *et al.*, 2010; Borges *et al.*, 2014a; Tagliapietra *et al.*, 2021). Molecular data from previous studies have revealed two cryptic species, the NEA form, identified as the "true" *L. pedicellatus* described by Quatrefages in 1849 (Borges *et al.*, 2012), and a cryptic sister species, *L. mersinensis,* found in Turkey (Borges & Merckelbach, 2018). Without molecular data or the presence of gravid females in the Tangier samples, species identification remains uncertain. Indeed, Treneman *et al.*(pers. commun.)

showed that *L. mersinensis* is a short-term larviparous species, whereas *L. pedicellatus* is a long-term larviparous–a difference that could aid identification in future studies. The inability to definitively identify these specimens' limits inferences about their origin, as they may originate from either the Mediterranean or the NEA.

Some pallets identified as *Lyrodus* cf. *pedicellatus* exhibited horizontal striations on the calcareous inner face (Fig. 5B and D), possibly indicating erosion. However, these pallets could also belong to juvenile specimens of *Bankia carinata*. The pallets of young *B. carinata* closely resemble those of *L. pedicellatus*, with the key difference being that the calcareous portion of the blade in *B. carinata* features fused cones covered by a single periostracum (see Figure 22 in Turner, 1966 and Figure 4C in Treneman *et al.*, 2018), which is similar to the horizontal striations observed. This suggests that the *Lyrodus* cf. *pedicellatus* specimens in this study may represent two species, given that different species can infest the same piece of wood (Bobat, 1995; Borges *et al.*, 2014a; Tagliapietra *et al.*, 2021).

*Teredo bartschi* occurs along both the Mediterranean and the NEA coasts (Borges *et al.*, 2014b; Tagliapietra *et al.*, 2021). While its presence in the Mediterranean was estimated to date back around a century (Tagliapietra *et al.*, 2021), the evidence remains inconclusive. Tagliapietra *et al.* (2021) regarded *Teredo aegyptia* – now considered a synonym of *T. bartschi*–as the earliest Mediterranean records; however, this specimen was actually collected in the Suez Canal by Roch & Moll (1935; see Tables I and II). As a result, Borges *et al.* (2014b) classified *T. bartschi* as a Lessepsian migrant, not the first Mediterranean record. The earliest confirmed Mediterranean record comes from Haifa, Israel, in the 1960s (catalog number Malacology 169815, MCZBASE, 2024). Notably, all other catalog numbers provided by Tagliapietra *et al.* (2021) for the Mediterranean are from specimens collected in the Red Sea.

Following the 1960s record from Haifa, no reports of *T. bartschi* in the Mediterranean emerged until 2002 in southern Turkey (Borges *et al.*, 2014b) and then in 2007 in Venice, Italy (Tagliapietra *et al.*, 2021). The species is now considered established in the Mediterranean. Its presence in Tangier suggests a westward expansion in the Mediterranean, although the full extent of this spread remains unknown.

In the NEA, *T. bartschi* has been reported in Spain and Portugal, but its origins remain uncertain (Borges *et al.*, 2014; Tagliapietra *et al.*, 2021). Surface currents from Gibraltar may facilitate the introduction of both *T. bartschi* and *L. pedicellatus* into the western Mediterranean from the Atlantic (Tagliapietra *et al.*, 2021), though molecular confirmation is needed.

*T. bartschi* is considered a significant invasive species in the Mediterranean (Tagliapietra *et al.*, 2021) and should be closely monitored due to its potential to cause significant damage, as seen in Venice, where it has become the dominant teredinid species. Given the adaptability of both *T. bartschi* and *L. pedicellatus*, their geographical range is likely to expand further with rising water temperatures, especially in vulnerable areas like the western Mediterranean basin (Tagliapietra *et al.*, 2021). Furthermore, these species are long-term brooders that release larvae that are ready to settle. This reproductive strategy not only supports the persistence of shipworm colonies in the port of Tangier but also underscores the importance of understanding their adaptive mechanisms.

As shipworms continue to adapt to changing marine conditions, effective management strategies will rely on a deeper understanding of these species and a multifaced approach combining prevention, early detection, and control measures. Key actions include implementing marine monitoring programs, reducing driftwood accumulation, and enforcing stricter ship maintenance protocols, such as hull cleaning and improved ballast water management. Enhanced regional cooperation on monitoring, regulations, and response strategies is crucial to limiting the threat posed by these destructive species. Traditional protection methods have proven inadequate, failing in 65% of the boats, underscoring the need for more effective alternatives. One option is transitioning to polyester or other non-wooden hull materials; however, these require higher initial investments, are less customisable, and are environmentally problematic since polyester is non-recyclable (FAO, 1991). Another possibility is the use of preservative-treated wood, though many biocidal preservatives are legally restricted (Klüppel *et al.*, 2015). Wood modification treatments, which are non-toxic and enhance timber durability against teredinids (Hill, 2011; Westin *et al.*, 2006; Klüppel *et al.*, 2015), present a promising alternative but are primarily used in marina decks and yachts. Unfortunately, these advances materials and treatments are neither locally available nor affordable for artisanal fishermen, creating significant barriers to their adoption and complicating efforts to mitigate shipworm impacts effectively.

## Acknowledgements

We would like to express our sincere gratitude to the National Fisheries Office (Office National des Pêches) in Tangier for their collaboration throughout this study. We are especially grateful to the artisanal fishermen and carpenters of the port of Tangier; whose cooperation and insights were essential to the success of our research. We also extend our thanks to the National Institute of Fisheries Research (INRH Centre Régional de Tanger) for their valuable support and contributions.

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