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Habitat characterization, anthropogenic impacts and conservation of rhodolith beds off southeastern Malta

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Abstract

1. Rhodolith beds, including maerl, are structurally complex perennial habitats that support a high species diversity but are threatened by numerous human activities, particularly in the Mediterranean Sea. Despite their global ecological importance, increased research efforts are needed to facilitate development of effective measures to conserve these habitats.
2. Two areas hosting rhodolith beds are known to occur off the coast of Malta (central Mediterranean), but only one has been previously studied. Through analysis of video footage collected from 56 different stations coupled with a desk study on human activities, the present study characterized the rhodolith bed located off the southeastern coast of Malta, including its extent, rhodolith morphotype composition, associated megabiota and impacts of anthropogenic activities thereon.
3. The bed occurred at depths of 60–95 m and covered an area of approximately 200 km^2, making it the second most extensive rhodolith area reported for the Mediterranean to date. It was dominated by spherical and branched rhodoliths whose cover reached a maximum of 74% but was more often <50%, similar to other Mediterranean rhodolith beds. A total of 84 different megafaunal species were recorded, suggesting that the diversity of megafauna associated with rhodolith bed habitats has been previously underestimated. A number of human activities, including extensive vessel anchoring and officially designated areas for aquaculture, bunkering and trawling, overlap with the mapped rhodolith distribution, highlighting the risk of habitat degradation.
4. A holistic approach to the management of all the competing activities and interests relative to the southeastern coast of Malta that gives due consideration to this newly characterized rhodolith bed and the threats it faces is therefore recommended. The legal framework and policy recommendations for better conservation of rhodolith bed habitats in the Mediterranean and European Seas are also discussed.

KEYWORDS
biogenic habitat, central Mediterranean, conservation, coralline algae, epibenthos, habitat mapping, maerl, rhodophyta

1 | INTRODUCTION

Rhodoliths are unattached nodules formed by calcareous red algae that can take various forms and sizes, generally with a mean diameter of 2–250 mm (Bosellini & Ginsburg, 1971; Ginsburg & Bosellini, 1973). Two main types occur: those where the algal thallus forms the entire nodule and those where the red alga settles on a sediment granule and then grows to completely encrust it. Rhodoliths are known to have a very wide geographical distribution, having been recorded from polar to tropical environments (Foster, 2001). The water depth at which rhodoliths occur varies from one area to another, mostly depending on the degree of light penetration. Generally, rhodoliths are found in the mesophotic zone but have been recorded at depths of 1–10 m in turbid waters off the British Isles (Irvine & Chamberlain, 1994), as well as at a water depth of 290 m in the Bahamas (Littler et al., 1991). In the Mediterranean Sea, where water transparency is relatively high, rhodoliths primarily occur at depths of 35–70 m but can also be found in very shallow (<2 m) and much deeper (150 m) waters (Aguilar et al., 2009; Basso et al., 2017; Pierri et al., 2024).

Accumulations of rhodoliths create a distinct habitat known as a rhodolith bed. Recently, in order to standardize monitoring of this habitat across the Mediterranean Sea, Basso et al. (2016) defined a rhodolith bed as an area with more than 10% cover of live rhodoliths, over a minimum surface area of 500 m^2. Over the past years, the term 'maerl' has often been used as a synonym of 'rhodolith bed'. However, maerl was originally described as a specific type of rhodolith bed composed of living and dead coralline algae with branched twig-like thalli that are sometimes interlocking (Huve, 1956; Jacquotte, 1962). Other rhodolith morphotypes with different degrees of branching, including unbranched spherical nodules, also accumulate to give rhodolith beds. Thus, while rhodolith beds include maerl in their definition, the opposite is not true (Rendina et al., 2022). The use of these two terms interchangeably in previous studies implies that rhodolith beds and maerl have been dealt with as an artificially homogenous category, which could have led to an ambiguous interpretation of their ecology (Martin et al., 2014).

1.1 | Ecological importance, threats and legal framework

Rhodolith beds are structurally complex perennial habitats that support a high number of species, which is mostly attributable to their three-dimensional complex structure (Barberá et al., 2003). Picard (1965) was one of the first to highlight Mediterranean rhodolith beds as a hotspot of biodiversity. Subsequently, numerous other studies stressed the ecological importance and need for conservation of rhodolith beds, in view of their contribution to productivity and the high degree of species and trophic group diversity they support (Barberá et al., 2003; Tuya et al., 2023). The high structural complexity of this habitat enhances the provision of shelter, food and nursery function for a number of species, several of which are of high commercial importance. In addition to this, rhodolith beds are also known to play a critical role in climate regulation since they are important centres for carbonate production and potentially act as a carbon sink (Martin & Gattuso, 2009; van der Heijden & Kamenos, 2017; but see Macreadie et al., 2017). They are now considered to be of ecological importance on a global scale, providing several ecosystem services such as biodiversity provision and climate change mitigation, but which require increased research efforts in order to facilitate development of effective conservation measures (Tuya et al., 2023).

In the past two decades, rhodolith beds have been recognized as non-renewable resources that are being threatened by numerous human activities (Basso et al., 2016). These include coastal structures causing hydromorphological changes that can result in burial of rhodoliths due to increases in sedimentation; effluent discharges and disposal of waste at sea that can reduce water quality; aquaculture, which can lead to eutrophication; dredging, anchoring and bottom trawling, which have direct physical impacts on rhodoliths by destroying the productive surface layer of the algal thallus; introduction of alien species that interfere with rhodolith bed functioning, such as the rhodophyte *Womersleyella setacea* in the Mediterranean; and increased ocean acidification as a result of climate change which may interfere with calcite production in calcifying organisms (Barberá et al., 2003; Sciberras et al., 2009).

Trawling in particular disturbs benthic communities by resuspending sediments, damaging biogenic structures, reducing faunal abundance, biomass and diversity, and selecting for fauna with fast life histories (Hiddink et al., 2017). Rhodolith beds are particularly vulnerable since trawling may break up rhodoliths and reduce rhodolith cover, hence negatively impacting the associated biota (Bordehore et al., 2003). Trawling on rhodolith beds has been reported from several Mediterranean locations, including Alicante (Bordehore et al., 2000), Majorca (Massuti et al., 1996), Italy (Fournier et al., 2020) and Malta (Borg et al., 1998; Fournier et al., 2020).

The vulnerability of rhodolith bed habitats has been recognized in international, regional and national legislation. Maerl beds are listed in the Bern Convention on the Conservation of European Wildlife and Natural Habitats (European Community, 1982), and an 'Action Plan for the Protection of the Coralligenous and other Calcareous Bioconstructions in the Mediterranean' was adopted by the Contracting Parties to the Barcelona Convention in 2008, and updated in 2016 (UNEP-MAP-RAC/SPA, 2017). However, the latter is not binding for the Contracting Parties.

In European legislation, the Habitats Directive 92/43/EEC (European Council, 1992) and Council Regulation EC 1967/2006 (Council of the European Union, 2006) are the main tools that have been set up to safeguard this habitat. The Habitats Directive lists *Phymatolithon calcareum* and *Lithothamnion corallioides*, two maerl-forming species, in Annex V 'Species that are subject to commercial exploitation for which Member States need to ensure the necessary management measures' (European Council, 1992). By focusing specifically on maerl-forming species, the Habitats Directive does not afford protection to other types of rhodolith beds. Council Regulation EC 1967/2006 has banned specific fishing gear on maerl beds. In this regulation, maerl is defined as "a biogenic structure due to several species of coralline red algae (Corallinaceae), which have hard calcium skeletons and grow as unattached free-living branched, twig-like or nodule coralline algae on the sea bed, forming accumulations within the ripples of mudflats or sandflats sea beds. Maerl beds are usually composed of one or a variable combination of red algae, in particular, *Lithothamnion corallioides* and *Phymatolithon calcareum*" (Council of the European Union, 2006). By including both branched and unbranched rhodoliths in its definition of maerl, Council Regulation EC 1967/2006 effectively protects all types of rhodolith beds (not just maerl beds in the strict sense of the term). However, the legislation does not specify the minimum rhodolith density and coverage required for an area to be considered a 'bed'.

More recently, several European countries, including Malta, have incorporated rhodolith beds as representative of the broad benthic habitat type 'circalittoral sediments' in their national assessments of Good Environmental Status under the Marine Strategy Framework Directive (MSFD) (European Parliament & Council of the European Union, 2008), which is reviewed every 6 years (Environment and Resources Authority, 2020; Malta Environment and Planning Authority, 2013).

1.2 | Rhodoliths in Maltese waters

To date, two extensive rhodolith beds have been documented in Maltese waters (within the 25 nautical mile Fisheries Management Zone [FMZ] established by the European Union), at depths of approximately 40–100 m: one located off the northeastern coast of Malta near the rocky shoal of 'is-Sikka l-Bajda' that extends up to Gozo (Borg et al., 1998) and a second one first recorded in 2004 off the southeastern coast of Malta (Dimech et al., 2004). Even though Borg et al. (1998) were the first to provide scientific information on rhodolith beds in the Maltese Islands, the existence of this habitat had been known by fishers long before, due to the high productivity of commercial species associated with this habitat (Sciberras et al., 2009).

Detailed studies have been carried out on the rhodolith bed located off the northeastern coast of Malta (Deidun et al., 2022; Sciberras et al., 2009); in contrast, very little is known about the rhodolith bed that is located off the southeastern coast. Information on the spatial extent of the bed and on the type and density of rhodoliths is lacking, even though such knowledge is essential for management of this habitat. The present study was therefore carried out to characterize the rhodolith bed located off the southeastern coast of Malta, including its extent, rhodolith morphotype composition, associated megabiota and impacts of anthropogenic activities thereon, in order to guide conservation efforts.

2 | METHODS

2.1 | Video data collection

Benthic surveys off the southeastern coast of Malta were carried out using a Saab Seaeye Falcon DR remotely operated vehicle (ROV) deployed from the research catamaran *Oceana Ranger* in June to July 2015 and May to July 2016. ROV surveys were made at 56 stations having water depths of 50–120 m, in a broad area previously identified as potentially hosting rhodolith beds (Dimech et al., 2004). On average, each station was surveyed for around 25 minutes, covering an area of circa 450 m^2. The ROV was maintained around 1–2 m above the seabed during the surveys.

The ROV was equipped with high-definition (HD) and a low-definition (LD) cameras having a resolution of 1,920 × 1,080 and 720 × 480 pixels, respectively, with a 10X optical zoom, together with a tracking system able to simultaneously record the position and depth of the ROV. The LD video footage was recorded throughout the entire dive-time, but its resolution was insufficient to identify different rhodolith morphotypes. Filming using the HD camera was carried out at 0.5–2 min intervals and distributed over the duration of a given survey, and in particular when there was a change in the bottom type. A comparison of the LD and HD video footage confirmed that there were no changes in bottom type in the gaps between the available HD video clips, which were therefore considered to be representative of a given station and were used to map rhodolith distribution and collect biological data.

2.2 | Video analysis

For each HD video, a frame-grab was extracted systematically at approximately 30 s intervals, resulting in a total of 866 frame-grabs (still images). Such frame-grabs were taken when the ROV was moving over the seabed in an 'aerial view' (rather than when zooming in on a particular item) in order to a get a good representation of the general area. In cases when the ROV was stationary and hovering in the same place for more than 30 s, only one frame-grab was extracted. For each frame-grab taken, the GPS position, depth and time were tabulated, uniquely tagging each image. Using the image processing program ImageJ version 1.50i (Rasband, 2016), a 10 × 10 grid (with a total of 100 grid cells) was superimposed on each frame-grab to calculate the percentage area of the seabed covered by rhodoliths. Visibly pink rhodoliths were considered as 'live', while white/grey rhodoliths were classified as 'dead', with percentage cover recorded separately for the two categories.

The percentage cover of other species of live algae was also estimated since where ≥30% of the bottom was obscured by non-coralline algae, rhodoliths could not be mapped and characterized with certainty. Frame grabs with high densities of other algae were therefore excluded from further analysis. With the exception of one station, where a high cover of fleshy algae obscured the view of the seafloor throughout the transect, and four stations that had a high but non-continuous cover of fleshy algae, a ≥30% cover of non-coralline algae was only present intermittently.

The mean density of live rhodoliths at each station was estimated, and a map showing the spatial distribution and density of live rhodoliths was produced using the 'Kriging' geostatistical interpolation method in ArcGIS version 10.6.1 (ESRI, 2018). Compared to other interpolation methods, Kriging was considered superior since it is based on statistical models that take autocorrelation into account (ESRI, 2020).

In order to collect data on the morphology of the rhodoliths, additional frame grabs were taken whenever the ROV zoomed in close enough to the bottom to allow the observer to clearly distinguish the individual rhodoliths. Frame grabs were always taken at the point where the video frame was zoomed in on an area of approximately 1 m^2 in order to make the images comparable. Rhodoliths were classified into the six morphotypes using the classification established by Sciberras et al. (2009). The percentage cover of the different rhodolith morphotypes was calculated using the same method described above for rhodolith density and recorded together with the corresponding GPS position and depth.

To characterize the megafauna associated with rhodolith beds, all megafaunal individuals visible in the HD videos collected from stations having >10% mean cover of live rhodoliths were identified to the lowest possible taxon and counted. When morphologically distinct taxa were encountered but it was not possible to identify the species from the video footage, these were distinguished using codes (e.g., Porifera sp. A and Porifera sp. B). The area surveyed in each station was calculated from the ROV track, allowing estimation of taxon abundance.

2.3 | Anthropogenic impacts

In order to gain a holistic view of the anthropogenic impacts on the surveyed area, a number of spatial datasets were compiled from existing sources. These included the following:

- an offshore aquaculture zone, which was plotted using the geographical positions listed in the 'Notice to Mariners No. 12 of 2017' (Transport Malta, 2017);
- bunkering areas, plotted using geographical coordinates obtained from the Transport Malta website (Transport Malta, 2019);
- trawling zones specified in European legislation (Council Regulation EC 1967/2006) and subsequent amendments made by the Maltese national trawl management plan in Legal Notice 354 of 2013 (Government of Malta, 2013), obtained from the Malta Inspire Geoportal (Malta Information Technology Agency, 2019).

Other fishing activities taking place in the area were not considered since only limited data were available and trawling was considered most likely to impact benthic habitats. In order to gather data on vessels anchoring in the study area, the 'MarineTraffic' website (MarineTraffic, 2019) was accessed every 2 weeks between June 2018 and June 2019. This website allows filtering of vessels based on their moving status (underway or anchored/moored). During each visit, details on all the vessels indicated as anchored in the study area were collected, including the anchoring GPS position and the vessel name, Maritime Mobile Service Identity, vessel type and vessel tonnage.

3 | RESULTS

3.1 | Rhodolith bed characterization

Rhodolith cover varied between stations and ranged from 0 to 74%. A >10% live rhodolith cover was recorded in 25 of the surveyed stations, with 10 stations having 10–25% cover; 12 stations having 25–50% cover; and three stations having 50–74% cover. Rhodoliths were mostly present at depths of 60–95 m, with peak live rhodolith densities recorded at 78.5 m. The shallowest areas with relatively high densities of rhodoliths were at a depth of 53.7 m, while the deepest record was at 106.9 m, where very low live rhodolith densities were noted. Overall, the rhodolith bed (*sensu* Basso et al., 2016) covered an area of approximately 200 km^2. The vast majority of rhodoliths recorded in the area surveyed (≈97%) were alive.

High-density patches of rhodolith accumulations were found close to the coast and towards the northeast of the study area close to the FMZ boundary, with patches where rhodoliths had low coverage in between (Figure 1). Very low densities of rhodoliths, or none at all, were recorded from stations located in the south, southeast and north of the study area, particularly where the water depth approached or exceeded 100 m. The absence of rhodoliths along the northern and southern edges of the study area indicates that the bed does not extend further north or south. Relatively high rhodolith densities were recorded from stations located along the western edge of the study area, and it is therefore possible that the area with live rhodoliths extends further to the west than indicated in Figure 1. Morphotypes E and D were the most common overall in the surveyed area, followed by morphotypes C and B in order of decreasing abundance (Figure 2). Morphotype F was recorded at very low densities, while morphotype A was practically absent. However, morphotype A consists of very thin twig-like structures that are often found embedded within the detritic bottom and hence not easily seen in ROV footage.

The main non-coralline algal species identified from the ROV stations considered collectively were *Flabellia petiolata*, *Zonaria tournefortii* and *Dictyota dichotoma*. Dense cover (≥30%) by these algae was mainly recorded in the western part of the study area (at depths of 61 to 77 m). At one station located close to the western edge of the survey area, dense growth of *Flabellia petiolata* obscured the view of the bottom throughout the ROV transect so rhodolith density could not be measured there, while four other stations also had a relatively high algal cover but also had areas with exposed rhodoliths (Figure 1). Throughout the study area, non-coralline algae were only present at water depths down to 80 m and therefore did

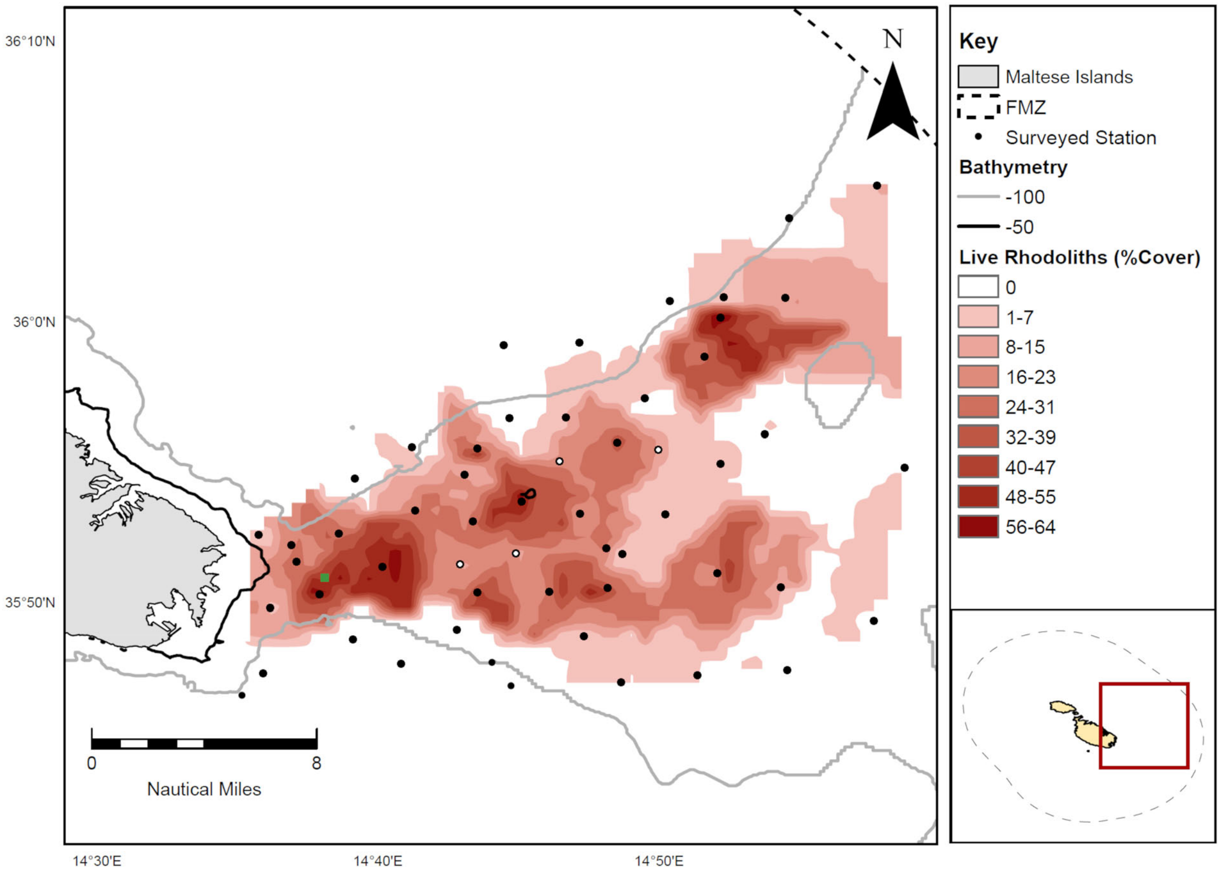
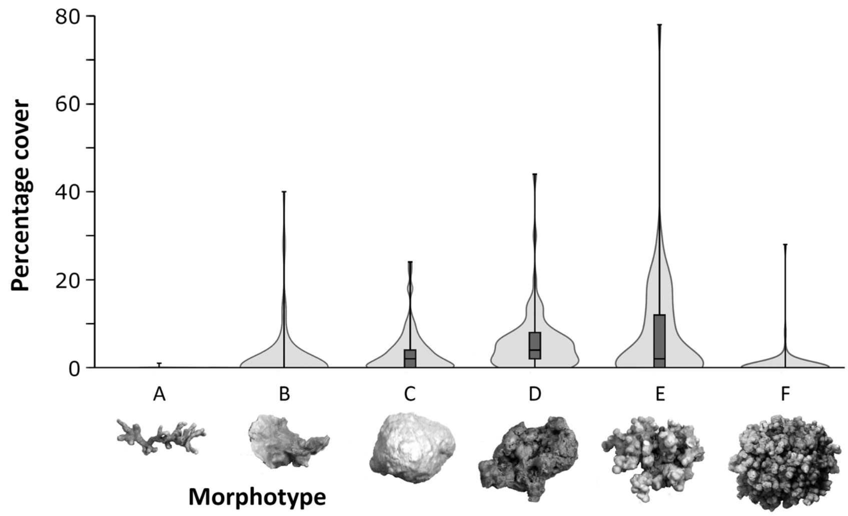


FIGURE 1 Live rhodolith density (% cover) within the surveyed area generated via 'Kriging' interpolation of the densities recorded at the surveyed stations. Data from one of the stations (green square) were not included since the bottom was obscured by non-coralline algae throughout the transect, precluding accurate estimation of the rhodolith cover. Rhodolith % cover at four other stations (open circles) may be underestimated due to a high cover of fleshy algae present there. The boundary of the 25 nautical mile Fisheries Management Zone (FMZ) established by the European Union is also shown.

FIGURE 2 Percentage cover for each of the six rhodolith morphotypes.



not extend as much offshore as the rhodoliths. No fleshy algae were recorded in the south, east and northeast of the surveyed area, except for a small patch in the northeast, which overlapped with an area of high rhodolith density.

A total of 84 different species of megafauna were recorded in association with the rhodolith beds, belonging to the Porifera (15 species), Cnidaria (16 species), Polychaeta (5 species), Phoronida (1 species), Mollusca (7 species), Crustacea (3 species), Echinodermata

(13 species), Bryozoa (5 species), Tunicata (4 species), Elasmobranchii (1 species) and Actinopterygii (14 species) (Table S1). Echinoderms were the most common taxon, with the echinoid *Stylocidaris affinis* present at all 25 stations that had >10% mean cover of live rhodoliths, while the crinoid *Antedon mediterranea* and the echinoid *Centrostephanus longispinus* were recorded from 60–65% of these stations (Table 1). On the other hand, 45 of the species were only recorded from a single station.

3.2 | Anthropogenic impacts

Biweekly assessments between June 2018 and June 2019 recorded 1,047 vessels anchored within the study area (Figure 3). The majority of these were located beyond the 12 nautical mile boundary, which marks the boundary of the territorial waters of the Maltese Islands. A considerable number of vessels were also anchored in the designated bunkering areas or in the vicinity of the aquaculture zone. Many of these vessels were anchored in areas where live rhodolith accumulations were present. The aquaculture zone also overlaps with a dense patch of rhodoliths, although the highest rhodolith density is located just beyond the zone's boundary. A significant proportion of the live rhodoliths occurred within the large trawling zone located off the southeastern coast of Malta (Figure 4). Trawling marks were also evident in certain areas in the video footage analysed during the present study (Figure 5).

TABLE 1 Main megafaunal species recorded from the 25 stations that had rhodolith beds (mean cover of live rhodoliths >10%), together with their frequency of occurrence (% of stations in which taxon was present) and mean ± standard deviation (SD) abundance.

Taxon	Frequency of occurrence (%)	Mean ± SD abundance (ind./100 m^2)
Porifera		
Axinella cannabina	8	1.09 ± 5.42
Haliclona sp.	36	11.30 ± 36.40
Cnidaria		
Paralcyonium spinulosum	8	2.10 ± 9.97
Polychaeta		
Bonellia viridis	24	0.10 ± 0.20
?*Protula*/*Apomatus* sp.	32	0.32 ± 0.60
Sabella sp.	36	0.24 ± 0.49
Mollusca		
Neopycnodonte cochlear	28	14.41 ± 49.81
Crustacea		
Inachus sp.	24	0.14 ± 0.34
Echinodermata		
Antedon mediterranea	60	5.30 ± 11.85
Centrostephanus longispinus	64	1.19 ± 1.90
Echinaster sepositus	48	0.14 ± 0.18
Hacelia attenuata	28	0.08 ± 0.15
Stylocidaris affinis	100	21.92 ± 17.44
Bryozoa		
Myriapora truncata	44	1.21 ± 2.56
Tunicata		
Rhopalaea neapolitana	32	0.20 ± 0.45
Actinopterygii		
Serranus cabrilla	52	0.28 ± 0.37

Note: Only species recorded from at least 5 stations or having a mean abundance >1 ind./100 m^2 are shown. The full list of megafauna is given in Table S1.

4 | DISCUSSION

4.1 | Habitat characteristics

While previous studies indicated that rhodolith accumulations were present off the southeastern coast of Malta (Dimech et al., 2004), the present work has provided the first detailed map of the spatial distribution of these rhodolith beds. Rhodoliths were found at depths beyond 100 m, and peak live rhodolith densities were recorded at depths of 78 m, which is slightly deeper than the 35–70 m at which Mediterranean rhodolith beds are commonly found (Basso et al., 2017), although beds at depths exceeding 100 m also occur in other places within the Mediterranean (e.g. Aguilar et al., 2009; Ingrassia et al., 2023; Valette-Sansevin et al., 2019) and elsewhere around the globe (e.g., Foster et al., 2013; Harvey et al., 2016; Littler et al., 1991).

The southeast Malta rhodolith bed covered an area of approximately 200 km^2, making it the second most extensive area with this habitat reported for the Mediterranean to date. A much larger rhodolith bed (918 km^2) is present in the Menorca Channel (Barberá et al., 2012). Significantly smaller rhodolith beds, covering areas of <10 km^2 in Tabarca (Spain), Campania and Apulia (Italy) (Bordehore et al., 2003; Chimienti et al., 2020; Rendina et al., 2020), and of 20–41 km^2 in northeast Malta, Lampedusa and Sardinia (Bracchi et al., 2022; Maggio et al., 2022; Sciberras et al., 2009), occur elsewhere in the Mediterranean. The Maltese and Menorcan beds are also large at a European scale, since most rhodolith beds recorded from the north-western Atlantic are smaller than 50 km^2 (Hall-Spencer et al., 2010; Jardim et al., 2022; Neves et al., 2021). On the other hand, the world's largest rhodolith bed, located in in Abrolhos Shelf (Brazil), covers and area of 20,902 km^2—some 100 times greater than that of the southeast Malta rhodolith bed (Amado-Filho et al., 2012).

The density and morphology (shape and branching characteristics) of rhodoliths are highly variable and influenced by environmental conditions (Foster et al., 2013). The densities and morphologies recorded in the present work were similar to those found in other Mediterranean rhodolith beds. In common with the bed located off the northeastern coast of Malta (Deidun et al., 2022; Sciberras et al., 2009), rhodolith morphotypes D and E were the most

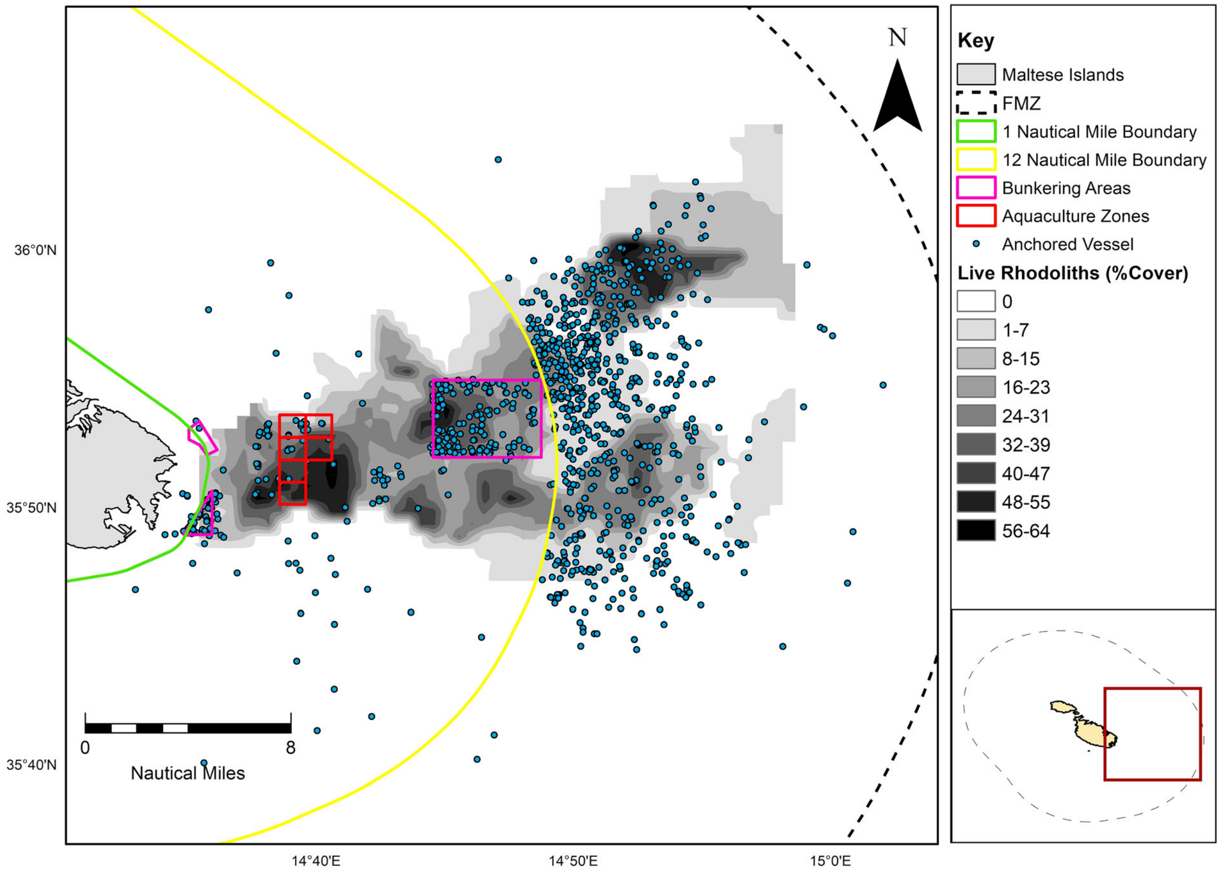


FIGURE 3 Anthropogenic activities in the study area superimposed on live rhodolith density, including anchored vessels, offshore aquaculture zone, vessel bunkering areas and trawling zones. The 1, 12 and 25 nautical miles boundaries are also indicated.

abundant, while the absence of morphotype A is probably an artefact attributable to its low visibility in ROV imagery. Rhodolith cover reached a peak of 74% but was more often found at <50%, which is comparable with findings from the Spanish coast, Sardinia, Campania and Apulia, where maximum values ranged between 43% and 66% (Bracchi et al., 2022; Chimienti et al., 2020; Illa-López et al., 2023; Rendina et al., 2020). An even denser bed, with >87% rhodolith cover, occurs in Lampedusa (Maggio et al., 2022).

Rhodolith beds are known to support a high diversity of associated fauna, including macroalgae, epifauna and infauna, as well as fish (Moura et al., 2021; Nelson et al., 2014; Neves & Costa, 2022). In the Mediterranean, crustaceans, polychaetes and sometimes molluscs are the main contributors to faunal diversity (Bordehore et al., 2003; Deidun et al., 2022; Maggio et al., 2022; Sciberras et al., 2009). Sponges, cnidarians, echinoderms and fishes had the highest number of species in the present study, but these results are not directly comparable to those of other studies, given that the latter mainly focused on macrobiota collected through grab sampling, in contrast to the visual observation of megabiota in ROV footage used here. Only Deidun et al. (2022) and Illa-López et al. (2023) conducted ROV surveys for megabenthic fauna, recording 6 and 119 different taxa, respectively, with echinoderms dominating in both cases. The present findings of 84 different megafaunal species corroborate those of Illa-López et al. (2023) and indicate that the diversity of megafauna associated with rhodolith bed habitats has been previously underestimated.

A rather impoverished non-coralline algal diversity was recorded from the southeast Malta rhodolith bed, dominated by *Flabellia petiolata* followed by *Zonaria tournefortii*, mirroring the current situation on the bed off the northeastern coast of Malta (Deidun et al., 2022). Significantly higher algal diversities with 117–165 species have been documented elsewhere (e.g., Bordehore et al., 2003; Mannino et al., 2002). A relatively high algal diversity (87 species) has also been previously recorded from the rhodolith bed in northeast Malta, although the dominant species was still *Flabellia petiolata* (Sciberras et al., 2009). When this species grows profusely on rhodoliths, as noted in some areas during the present study, it changes the nature of the bottom since it aggregates sediment and binds rhodoliths together, while at the same time providing new surfaces (the stabilized sediment and algal laminae). Consequently, it can favour settlement of epibiota while hindering interstitial species, resulting in changes to the benthic assemblages (Deidun et al., 2022; Sciberras et al., 2009). Extensive growth of *Flabellia petiolata* and other rhodolith-binding species can also be detrimental to the rhodolith-forming corallines through shading out and by preventing the nodules from turning, which is a requirement for rhodolith

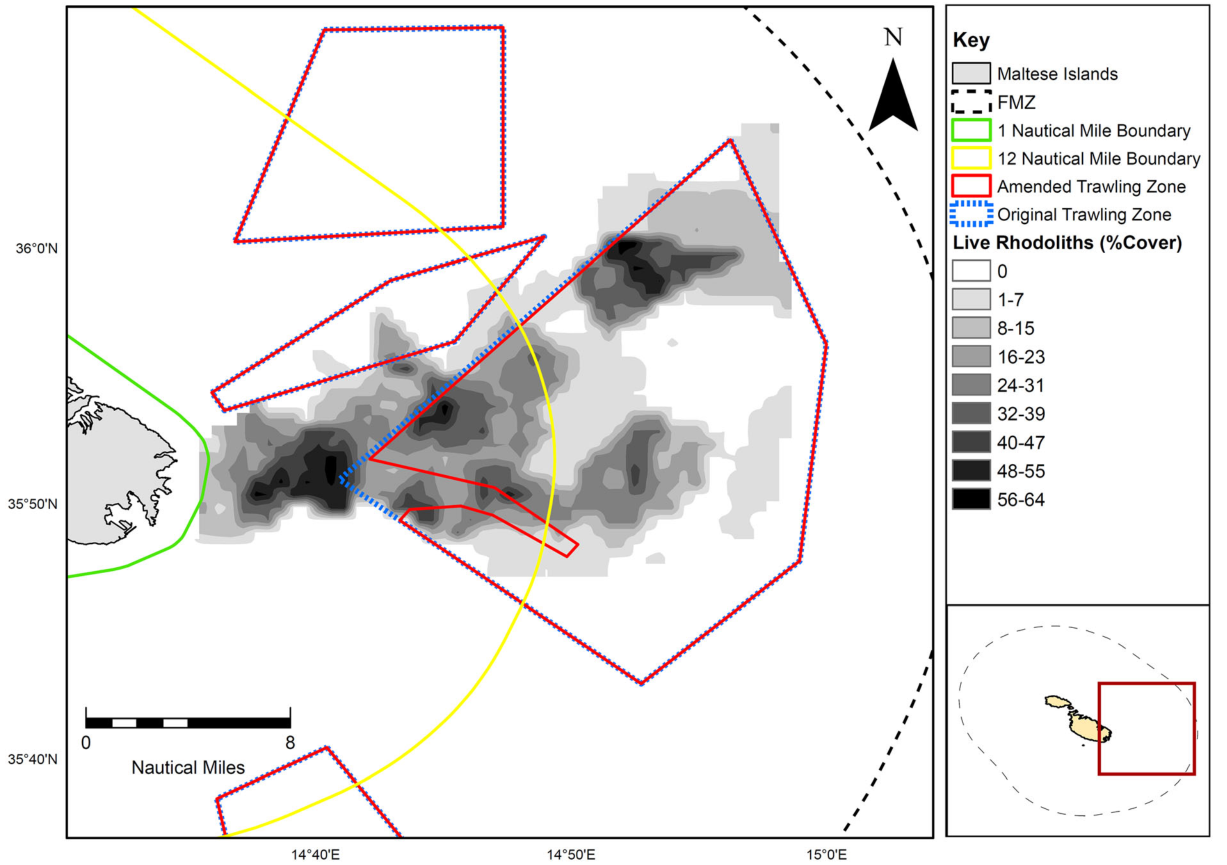


FIGURE 4 Trawling zones in the study area superimposed on live rhodolith density. The original boundary of the trawling zone later amended by the Maltese national trawl management plan in 2013 is shown with a dashed line. The 1, 12 and 25 nautical miles boundaries are also indicated.

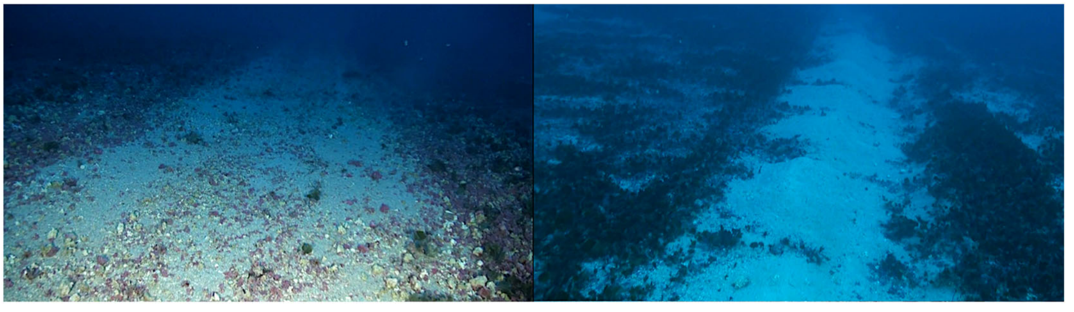


FIGURE 5 Areas with evident linear furrows made by bottom trawling.

survival (Sciberras et al., 2009). Additionally, from a research point of view, high densities of non-rhodolith forming algae can also interfere with mapping of rhodolith coverage (Rocha et al., 2020).

Collection of grab samples through future surveys could provide more comprehensive information on the identity of the rhodolith-forming algal species, the rhodolith structure (e.g., geniculate vs. non-geniculate) and morphology, and on cryptic biota associated with the southeast Malta rhodolith bed, enabling direct comparison with other rhodolith beds sampled in this manner, including that located off the northeastern coast of Malta studied by Sciberras et al. (2009) and Deidun et al. (2022). The extent to which the distribution of rhodoliths overlaps with other algal species, in particular *Flabellia petiolata*, which was observed during a number of dives in the present study, could also be revealed by grab samples. This would facilitate assessment of whether overgrowth by other algal species influences the structure and function of the rhodolith beds. Further research is also required to gather detailed information on how various parameters, such as light availability, currents, nutrient levels and temperature, affect the spatial and bathymetric distribution of rhodoliths in Maltese waters.

4.2 | Is this area also a maerl bed?

Since Council Regulation EC 1967/2006 bans the use of specific fishing gear on maerl beds, whether the rhodolith beds in the study area qualify as maerl is not simply academic but has legal implications. As noted in the above, the definition of maerl beds in Council Regulation EC 1967/2006 is broad and essentially includes all types of rhodolith beds. There is therefore little doubt that the study area includes maerl beds as defined in this regulation.

From a scientific point of view, maerl in the strict sense of the term has been defined as a specific type of rhodolith bed composed of non-nucleated, unattached coralline algae with branched twig-like thalli that are sometimes interlocking (Basso et al., 2016). Within the Mediterranean, *Phymatolithon calcareum* and *Lithothamnion corallioides* are the dominant maerl-forming species (Basso et al., 2016). To identify whether the rhodolith accumulations found within the area of study can be considered to be maerl under this definition, information on the species of rhodolith forming-algae and their morphology is thus required. The present study was based exclusively on ROV footage and consequently identification of the coralline algae to species level was not possible since this requires examination of microscopic structures, especially of the conceptacles (Lanfranco et al., 1999). However, the maerl-forming species *Phymatolithon calcareum* and *Lithothamnion corallioides* were recorded from the rhodolith bed located off the northeastern coast of the Maltese Islands (Sciberras et al., 2009), where Morphotypes D, E and F were the predominant rhodolith shapes. Similarly, Morphotypes E (with short finger-like branches) and D (with a rugged surface) were the commonest morphotypes recorded in the present study area. In addition, *Phymatolithon calcareum* was recorded during a study made as part of an Environment Impact Assessment in connection with the aquaculture zone located in this area (Adi Associates Environmental Consultants Ltd., 2005). Given the known presence of *Phymatolithon calcareum* in the area and dominance of rhodoliths with finger-like branches, at least parts of the rhodolith bed surveyed during the present work could also be classified as a maerl bed in the strict sense of the term as defined by Basso et al. (2016).

4.3 | Anthropogenic impacts and management implications

The anthropogenic activities that can have impacts on the rhodoliths found in the area of study appear to be substantial (Figure 3); in particular, anchoring and trawling can be expected to negatively impact the rhodoliths by causing direct physical damage to the productive algal thallus.

The present study for the first time provides information on the extensive vessel anchoring that takes place off the southeastern Maltese coast. The shallow area just outside Maltese territorial waters is known locally as ‘Hurd Bank’ and is a convenient location for ships to stop since it is located just off the Central Mediterranean's busiest shipping lane. This is concerning since scientific studies have shown that rhodolith beds disturbed by mooring activities support assemblages that are less abundant, diverse and stable than those in undisturbed beds (Gabara et al., 2018).

Rhodoliths located close to aquaculture cages may also be impacted through smothering from uneaten fish feed and its decomposition products, through increased sedimentation rates and nutrient inputs, as well as by direct physical damage from mooring blocks that are used to anchor the cages (Barberá et al., 2003; Sanz-Lázaro et al., 2011). The extent of these impacts will depend on the management of these mariculture operations and local hydrodynamic conditions. The video footage that was used to plot the spatial distribution of the rhodoliths during the present study was collected in 2015 and 2016, just before the offshore aquaculture zone was extended southwards in 2017 (Transport Malta, 2017). Therefore, there may now be additional impacts due to this extension. Since some of the highest densities of live rhodoliths were recorded in the area where the extension subsequently took place, assessment of changes in the condition of the rhodolith beds present in this region is warranted; the present results can serve as a baseline against which to gauge any new impacts.

In the western Mediterranean, bottom otter trawling is an important anthropogenic impact on rhodoliths (Bordehore et al., 2003; Oliver, 1983). This activity is considered to be particularly destructive since, apart from the direct physical damage to the rhodoliths and the reduction of rhodolith cover, trawling also deposits sediment on live algal thalli, and on any associated biota that escape the trawl nets. This results in smothering of the habitat and subsequently inhibiting its recovery (Hall-Spencer, 2005). Depending on local hydrographic conditions, the impact of sedimentation may affect a much larger area than the actual trawl paths. A more indirect negative effect from trawl fishing may result from the dumping of discarded by-catch into the sea, which can lead to localized oxygen depletion (Jones, 1992).

Malta's update to the initial assessment pursuant to the MSFD assessed the trawling effort within the study area on the basis of fisheries data, as part of an overall assessment of the spatial extent and distribution of physical disturbance pressures on the seabed. In specific parts of the study area, trawling effort was in the range of 388–811 h over a 4-year period (2015–2018); this occurred in 13% of the trawl zone, based on effort data at a resolution of 25 km^2 grid cells. Conversely, the effort in other parts of the study area was either minimal or very low, with less than 25 trawling hours per year (Environment and Resources Authority, 2020). Trawl marks were also noted in areas with high rhodolith densities during the present work (Figure 5). However, precise information on the location of trawling lanes, and hence the spatial footprint of trawling taking into consideration sediment deposition, was not available to the authors as fisheries Vessel Monitoring System (VMS) data are not publicly accessible. Since this is the first detailed study of the rhodolith accumulations off the southeastern coast of Malta, the extent of impacts that the various anthropogenic activities taking place in this area have on the condition of this habitat could not be fully quantified. Although the percentage cover of live rhodoliths was found to be relatively high in some places, it is also evident that certain areas have been negatively impacted from anthropogenic pressures and specifically from trawling activities.

4.4 | The legal framework and policy context

In 2013, the Maltese fisheries management plan (Government of Malta, 2013) undertook a revision of the trawl zones in order to mitigate the impact of trawling activity on rhodolith beds, in line with the implementation of the European Union (EU) legislation, which bans fishing with trawl nets, dredges, shore seines or similar nets above coralligenous habitats and maerl (Council of the European Union, 2006). However, a comparison of the zones where trawling has been allowed since 2013 and the interpolated distribution of the rhodolith beds mapped during the present study shows that only a small part of the trawl zone overlapping with an area of rhodolith beds was closed (Figure 4). Thus, the currently designated trawling zone still overlaps with rhodolith beds, even though monitoring by local authorities indicates that there is no significant trawling activity within the estimated high density rhodolith bed areas (Department of Fisheries and Aquaculture, Malta, personal communication October 2023). Nevertheless, the present study indicates that large parts of the mapped rhodolith beds do in fact fall under the definition of 'maerl bed' given in Council Regulation EC 1967/2006; therefore, the location of the legal trawl zones should be reviewed once again by the relevant authorities. This could be done as part of the revision of the bottom otter trawl management plan, which had been planned for 2016 (Article 6.7; Government of Malta, 2013), but it is still in progress.

One key conservation measure would be for the definitions of any future fisheries legislation on technical measures replacing Article 4 of Council Regulation EC 1967/2006 to refer to 'rhodolith beds' irrespective of the rhodolith-forming species or their morphology. Such a definition should further specify the minimum rhodolith density and coverage required for an area to be considered a rhodolith/maerl 'bed', instead of only referring to an area characterized by the 'dominant presence' of rhodoliths. The definition of rhodolith beds as areas with more than 10% live rhodolith cover over a minimum surface area of 500 m^2 given by Basso et al. (2016) provides useful guidance in this regard. Although information on the effects of environmental parameters on the functioning of rhodolith beds exists (e.g., Otero-Ferrer et al., 2020), studies that have specifically investigated the relationship between the density of rhodoliths and the diversity of associated biota are lacking.

In addition to this, to date, the only maerl-forming species protected under the Habitats Directive are *Phymatolithon calcareum* and *Lithothamnion corallioides*, which are both 'species of community interest whose taking in the wild and exploitation may be subject to management measures' listed in Annex V (European Council, 1992). The reason behind the inclusion of these two Atlantic species in Annex V of this Directive is that these two maerl-forming species have been harvested in Northern Europe for many years for use as agricultural soil conditioners, animal food additives and also in water filtration systems (Hall-Spencer et al., 2010). In fact, these activities have led to the deterioration of this habitat in several areas, such as France (Grall & Hall-Spencer, 2003) and Ireland (de Grave & Whitaker, 1999).

The protection of these species through this Directive is thus limited to human exploitation, even though this is rarely an issue in the Mediterranean where rhodolith beds are found in much deeper waters compared to the Atlantic. Protection against other potential sources of human impact, such as aquaculture activities or extensive anchoring, is required in the Mediterranean context. It would therefore be more relevant for rhodolith beds as defined by Basso et al. (2016) to be included in Annex I as 'natural habitat types of community interest whose conservation requires the designation of Special Areas of Conservations (SACs)' (European Council, 1992).

On a Mediterranean scale, the Protocol Concerning Specially Protected Areas and Biological Diversity in the Mediterranean (SPA/BD Protocol) of the Barcelona Convention recommends protection measures in order to safeguard elements of biological diversity through Action Plans and the designation of Specially Protected Areas of Mediterranean Importance (SPAMIs), which also include transboundary areas (UNEP-MAP, 2019). The inclusion of rhodolith-forming species in Annex II of the SPA/BD Protocol (list of endangered or threatened species) would ensure stricter measures to protect rhodolith beds. Maerl and rhodolith bottoms have been included in the 'Updated Reference List of Marine Habitat Types for the Selection of Sites to be Included in the National Inventories of Natural Sites of Conservation Interest in the Mediterranean' (SPA/RAC, 2019).

Characterization of the rhodolith bed located off the southeastern coast of Malta has revealed that this habitat is at risk of degradation from a number of human activities, including extensive vessel anchoring and the officially designated trawl zone, bunkering area and aquaculture zone that overlap with the mapped rhodolith distribution. While acknowledging that complete cessation of such activities may be impossible for socio-economic reasons, there is clearly a need for implementing measures to safeguard the habitats of high conservation interest present in the region. A holistic approach to the management of all the competing activities and interests relative to the southeastern coast of Malta may be achieved through a revision of Malta's maritime spatial plan as part of the implementation of Directive 2014/89/EU on marine spatial planning, giving due consideration not only to social and economic activities but also to newly discovered environmental aspects.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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