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The invasive thermophilic red alga *Lophocladia lallemandii* reaches the Port-Cros National Park (France, northwestern Mediterranean)

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Abstract: The Mediterranean Sea is worldwide the area most hit by introduced species. The Suez Canal (inflow of Lessepsian species) and shellfish aquaculture are the main vectors of introduction, in addition to shipping (fouling, clinging and ballast waters). *Lophocladia lallemandii*, a red alga (Rhodobionta) native to the Red Sea and the Indian Ocean, is invasive in the Mediterranean. Hitherto confined to the eastern basin and to the south-western basin, it has been collected at the Port-Cros Archipelago (Port-Cros National Park), in the shallow infralittoral zone, 3-8 m depth. The maritime traffic (e.g. yachting) between already invaded areas (e.g. Balearic Islands) and Port-Cros, and the current warming of the Mediterranean probably facilitated the northwards spread of this thermophilic species.
Keywords: invasive species, global warming, *Lophocladia lallemandii*, national Park, Provence.

***Résumé*. L'algue rouge thermophile et invasive *Lophocladia lallemandii* est arrivée dans le Parc national de Port-Cros (France, Méditerranée nord-occidentale**). La mer Méditerranée est la région du monde qui héberge le plus grand nombre d'espèces introduites. Le canal de Suez (espèces dites 'lessepsiennes') et l'aquaculture des mollusques constituent les principaux vecteurs d'introduction, en plus de la navigation (*fouling*, *clinging* et eaux de ballast). *Lophocladia lallemandii*, une algue rouge (Rhodobionta) originaire de la mer Rouge et de l'océan Indien, est invasive en Méditerranée. Jusqu'à maintenant confinée dans les eaux relativement chaudes du bassin oriental et du Sud du bassin occidental de la Méditerranée, elle a été découverte dans l'archipel de Port-Cros (Parc national de Port-Cros), dans l'étage infralittoral peu profond (3 à 8 m de profondeur). Le trafic maritime (e.g. navigation de plaisance) entre les zones déjà envahies (e.g. îles Baléares) et le réchauffement actuel des eaux méditerranéennes ont sans doute favorisé la progression vers le Nord de cette espèce thermophile.
Mots-clés : espèce invasive, *Lophocladia lallemandii*, Parc national, Provence, réchauffement global.

Introduction

The Mediterranean Sea is the area most hit worldwide by introduced species (Schaffelke *et al.,* 2006; Lejeusne *et al.,* 2010). A thousand or so Non-Indigenous Species (NIS) have been reported, more than 600 of them definitely introduced, i.e. self-reproducing in their new quarters (Zenetos *et al.*, 2010; Galil *et al.,* 2018). The two major vectors of introduction are the Suez Canal (in the eastern basin), which allows warm water species from the Red Sea and the

Indian Ocean to enter the eastern basin of the Mediterranean (the so-called Lessepsian species), and the shellfish aquaculture, mainly of the Japanese oyster *Magallana gigas* (Thunberg, 1793), through spat import, in the western basin, which allows cold affinity species from the north-eastern Pacific (mainly Japan and Korea) to colonize the Mediterranean. In addition, shipping (fouling and clinging on ship hulls and ballast water) is an important vector throughout the Mediterranean (Por, 1978; Boudouresque, 1999; Verlaque, 2001; Boudouresque and Verlaque, 2002a; Verlaque *et al.,* 2007; Boudouresque *et al.,* 2011; Verlaque *et al.,* 2015; Boudouresque *et al.,* 2016; Galil *et al.,* 2018).

As far as MPOs (Multicellular Photosynthetic Organisms, i.e. macrophytes) are concerned, 158 NIS have been reported in the Mediterranean in 2021 (Charles-François Boudouresque, unpublished data), as compared to only 117 in 2014 (Verlaque *et al.,* 2015), although the latter census was more selective than the former.

Invasive species are introduced species which are harmful for native species, ecosystems, human health and/or economic activities (Boudouresque and Verlaque, 2002b, 2012).

In addition to introduced species, thermophilic native species, once restricted to the warmest areas of the Mediterranean, the eastern basin and the southernmost areas, are spreading westwards and northwards, due to global warming, such as the green alga *Caulerpa prolifera* (Forsskål) Lamouroux, the Asteroidea *Ophidiaster ophidianus* (Lamarck, 1816), the teleosts *Thalassoma pavo* (Linnaeus, 1758), *Scorpaena maderensis* Valenciennes, 1833 and *Sparisoma cretense* (Linnaeus, 1758) (Francour *et al.,* 1994; Harmelin and Ruitton, 2010; Astruch *et al.,* 2016; Bianchi *et al.,* 2018; Astruch *et al.,* 2021).

Here, we report on the occurrence of *Lophocladia lallemandii* (Montagne) F. Schmitz (Rhodomelaceae, Rhodobionta, kingdom Archaeplastida) at La Gabinière Islet, Port-Cros Archipelago (eastern Provence, France, north-western Mediterranean Sea).

Material and methods

Lophocladia lallemandii was discovered on December 15th, 2021, during a dive to search for the possible recovery by young individuals of the Mediterranean endemic bivalve molluscan *Pinna nobilis* Linnaeus, 1758, after the mass mortality due to a unicellular parasite, probably introduced, *Haplosporidium pinnae* Catanese *et al*., 2018 (kingdom Rhizaria) (Catanese *et al*., 2018; Boudouresque *et al.,* 2020; Ruitton and Lefebvre, 2021).

Lophocladia lallemandii was observed by SR and DT at La Gabinière Islet (western side), Port-Cros Archipelago, one of the core areas of the Port-Cros National Park, Provence, France (Barcelo and Boudouresque, 2012; Boudouresque *et al.,* 2021). Fresh specimens were collected at 5 m depth for laboratory identification. Voucher dried

specimens of the collected material of *L. lallemandii* were deposited in the Marseille University herbarium (HCOM), university campus of Luminy, Marseille, France, with the following reference number: H8344.

Results

Lophocladia lallemandii formed apparently monospecific large patches over the substrate, a metamorphic rock (see Bronner, 1987, for local geology) (Fig. 1, 2). The species was observed between 3 and 8 m depth, forming several patches of variable size between 30 cm and 1 m in diameter. It appeared abundant, forming a relatively thick carpet, up to 10 cm high, in contrast with the rest of the algal assemblage, which is lower during the winter season, except for the seagrass *Posidonia oceanica* (Linnaeus) Delile.

The collected specimens presented all the distinguishing characteristics of *L. lallemandii*, as listed by Feldmann and Feldmann (1938) and Verlaque *et al.* (2015): a monopodial growth, the branching exogenous, with branches replacing a trichoblast, the axes with four pericentral cells, the axial cell narrow in transverse section, the segments short, the trichoblasts coloured and persistent, the tetrasporangial stichidia inserted on the basal cell of the trichoblasts, slightly spirally twisted and with one tetrasporangium per segment (Fig. 3, 4).

Figure 1. A patch of *Lophocladia lallemandii*, 6 m depth, at La Gabinière Islet (in the foreground). The diameter of the patch is ~70 cm. Top left in the background, a patch of the seagrass *Posidonia oceanica*. Photo © Sandrine Ruitton.

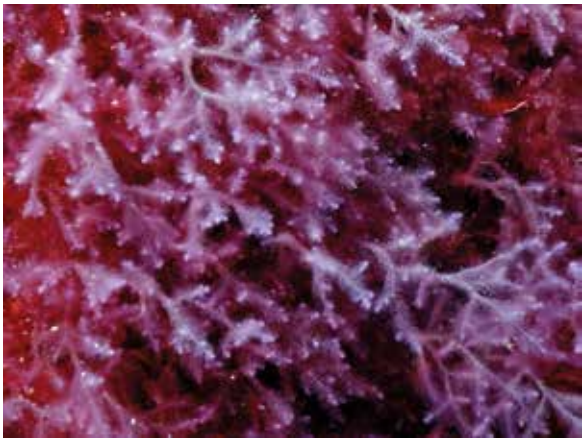

Figure 2. A closer view of a patch of *Lophocladia lallemandii* (see Fig. 1). Photo © Sandrine Ruitton.

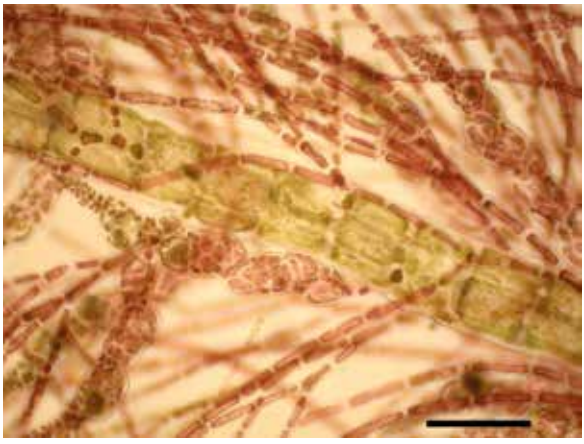

Figure 3. Portion of the axis, with coloured trichoblasts and stichidia (from specimen H8344 - La Gabinière Islet, 6 m depth). Scale bar: 200 µm. Photo © Marc Verlaque, courtesy of the author.

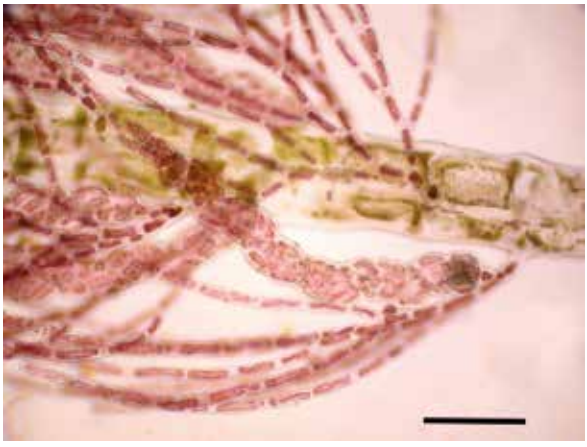

Figure 4. Portion of the axis, showing, on the bottom right side, the insertion of a twisted stichidium on the basal cell of a coloured trichoblast (from specimen H8344 - La Gabinière Islet, 6 m depth). Scale bar: 200 µm. Photo © Marc Verlaque, courtesy of the author.

Discussion and conclusions

The macrophyte flora of the Gulf of Hyères, including the Port-Cros Archipelago, has been thoroughly studied in the 1960-1970s (Belsher *et al.,* 1976; Coppejans, 1983). Among the 335 taxa recorded, *L. lallemandii* was definitely absent.

Lophocladia lallemandii is native to the Red Sea (where the type locality is located) and the Indian Ocean (Einav *et al.,* 2021). It entered the Mediterranean Sea *via* the Suez Canal and was first observed in Greece and Libya (Petersen, 1918), then in Algeria (Feldmann and Feldmann, 1938). It subsequently steadily spread to the whole eastern and south-western Mediterranean (Cebrian and Ballesteros, 2010; Verlaque *et al.,* 2015; El Zrelli *et al.,* 2021). The species was reported for the first time in 1969 along the coast of Italy (Occhipinti-Ambrogi *et al.,* 2011), but only recently has a large-scale invasion been reported (Bedini *et al.,* 2014; Tiberti *et al.,* 2021) off the islands of Pianosa and Ischia (west coast of Italy). The important maritime traffic (e.g. yachting) between already invaded areas (e.g. Balearic Islands, Italian and Spanish coasts) and Port-Cros, and the current warming of the Mediterranean probably facilitated the northwards spread of this thermophilic species.

Lophocladia lallemandii is strongly defended against herbivorous species by toxic chemicals, namely the cytotoxical lophocladine (alkaloid) (Gross *et al.,* 2005; Tomas *et al.,* 2011a, 2011b). It invaded and became dominant in Fucales forests of Tuscany (Bedini *et al.,* 2011, 2014) and is a stress factor for the giant pen shell *Pinna nobilis* (Box *et al.,* 2008, 2009) and the seagrass *Posidonia oceanica* (Sureda *et al.,* 2008). In the *P. oceanica* meadow, the mat of *L. lallemandii* can become so thick and dense that new leaves are entrapped within the mat, display chlorosis and sometimes die, together with the shoots of *P. oceanica* which they belong to (Ballesteros *et al.,* 2007).

As recently evidenced by the proliferation of the brown alga *Rugulopteryx okamurae* (E.Y. Dawson) I.K. Hwang, W.J. Lee & H.S. Kim (Phaeophyceae; kingdom Stramenopiles) in the Calanques National Park, near Marseille (western Provence, France) (Ruitton *et al.,* 2021), together with the present occurrence of *L. lallemandii* in the most remote and preserved zone of the Port-Cros National Park, and pinpointed by a host of authors (e.g. Simberloff, 2000; Guidetti *et al.,* 2014; Giakoumi *et al.,* 2019; Mannino and Balistreri, 2021; Tiberti *et al.,* 2021; Moodley *et al.,* 2022), invasive species do not respect the boundaries of Marine Protected Areas (MPAs).

We do not know how long *L. lallemandii* has been present in the Port-Cros Archipelago, nor if it is already widely present in the region. Is the occurrence transient, with the population unlikely to survive the winter, or does it indicate permanent establishment? How did it arrive in the Port-Cros Archipelago? By spores transported by the currents, or *via* the fouling on the hull of yachts? A further thorough survey is

needed to answer these questions. The appearance of *L. lallemandii* is after all unremarkable (a red filamentous alga) and a very small number of specialists are able to identify it. This underlines the importance of routine explorations, as well as of the close collaboration between the authorities of an MPA and scientists working in academic laboratories.

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