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NOTE

A NEW RECORD AND ERADICATION OF THE NORTHERN ATLANTIC ALGA *ASCOPHYLLUM NODOSUM* (PHAEOPHYCEAE) FROM SAN FRANCISCO BAY, CALIFORNIA, USA[1]

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A new record of the Northern Atlantic fucoid *Ascophyllum nodosum* (L.) Le Jolis (Knotted wrack) was discovered on a shoreline in San Francisco Bay, California during a survey of intertidal habitats in 2001–2002. The alga showed no signs of deterioration 2.5 months after its initial detection. The healthy condition, presence of receptacles with developing oogonia, potential for asexual reproduction, and ability to withstand environmental conditions, both inside the Bay and on the outer Pacific coast, prompted a multiagency eradication effort. Given the relatively small area of shoreline inhabited by the alga, in combination with its absence in 125 other surveyed locations, we decided that manual removal of the seaweed would be the most environmentally sensitive yet effective eradication approach. No *A. nodosum* has been detected at the site since December 2002, and the species is thought to have been locally eradicated. The site continues to be monitored to assess the success of the eradication efforts.

Key index words: **eradication; exotic; fucoid; invasion; marine; nonindigenous species**

We report the discovery and eradication of an Atlantic fucoid alga from an intertidal site in San Francisco Bay. On 6 September 2002 we discovered mats of free-living (without holdfasts) Knotted wrack, *Ascophyllum nodosum* (L.) Le Jolis in the mid- and high-intertidal zone near the Redwood City Marina in San Francisco Bay, California, USA (37°30.25′ N, 122° 12.86′ W). *Ascophyllum nodosum* is native to intertidal habitats of the North Atlantic Ocean. Specimens were identified by Paul Silva and Kathy Ann Miller as *A. nodosum* ecad *mackayi* (Turner) Holmes & Batters and have been deposited in the Jepson Herbarium at the University of California, Berkeley. Air bladders were reduced and infrequent; receptacles were uncommon but present and upon dissection were shown to contain developing oogonia. The habitat where the seaweed was found is engineered, composed of a sheltered, shallow, sloping beach with muddy substrate, scattered with riprap (approximately 25–50 cm diameter rocks). The riprap grades into a stand of cord grass, *Spartina* sp., and pickleweed, *Salicornia virginica* L. in the upper intertidal. An irrigated lawn and paved parking lot located just above the site provide a potential source of freshwater runoff to the intertidal below, possibly creating a microhabitat favorable to the formation of the ecad *mackayi*.

In the North Atlantic, *A. nodosum* inhabits a wide spectrum of environmental conditions and exhibits a broad latitudinal range, indicating an extensive potential geographic range on the Pacific coast of North America. *Ascophyllum nodosum* is found in North America from Baffin Island to Long Island Sound and in Europe from the Barents and White Seas south to Portugal (South and Hill 1970). *Ascophyllum nodosum* grows well under low to moderately high wave energy environments (Gibb 1957) and is tolerant of a broad range of salinities (0–40 psu; Chock 1975). Temperature tolerance is also considerable, as Newfoundland and New England populations of *A. nodosum* withstand icing in winter (South and Hill 1970, Mathieson et al.

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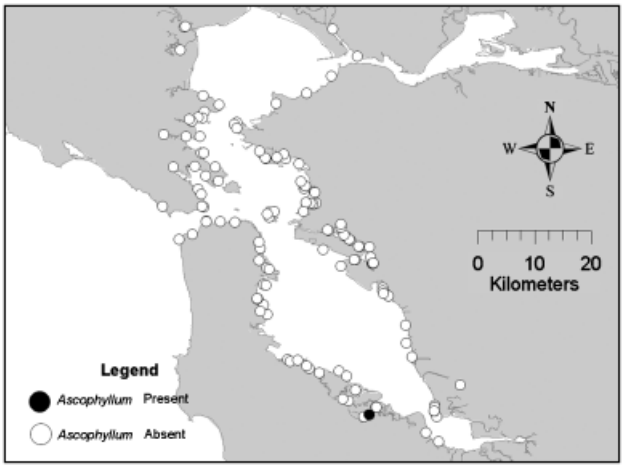

FIG. 1. Locations of intertidal surveys in San Francisco Bay (California, USA) completed between 1 June 2001 and 20 September 2002. The black circle marks the location of *Ascophyllum nodosum*, and white circles indicate locations that were surveyed but where *A. nodosum* was not detected.

1982) and can exist in ambient temperatures ranging from 0 to 24° C (Chock 1975).

Free-living *A. nodosum* ecad *mackayi* reproduces vegetatively but can form fertile receptacles and reproduce sexually, giving rise to the attached form of this alga (Gibb 1957). The reverse process also occurs: Holdfast-bearing *A. nodosum* transforms into free-living ecads when exposed to proper environmental conditions, indicating phenotypic plasticity of ecotypes rather than genetically based morphologies (Gibb 1957). In particular, Gibb (1957) described salinity regimes that included freshwater runoff alternating with saltwater inundation as the primary driver for the formation of *A. nodosum* ecad *mackayi*. In Scotland, ecad *mackayi* was shown to develop under natural environmental conditions where salinity fluctuated between high concentrations (>29 psu) and low concentrations (<9 psu). Salinities were greatest during rising and high tides and dropped rapidly during falling tides due to the increased influence of freshwater runoff (Gibb 1957). Other habitat requirements described include shelter from wave action and substrates that are flat to gently sloping and composed of sand, pebbles, or stones with or without a thin layer of sandy mud. The process of ecad *mackayi* development has been reported to occur slowly, taking up to several years to attain the most advanced stages (Gibb 1957).

In 2001–2002, during a San Francisco Bay-wide survey that included 126 intertidal locations, *A. nodosum* ecad *mackayi* was only encountered once, at Redwood City (Fig. 1). Densely branching mats of *A. nodosum* ecad *mackayi* occurred on the rocky substrata extending from the *Spartina* to just below the mid-intertidal zone. Salinity measurements at the Redwood City site ranged from 23.6 to 24.8 psu; however, these readings were confined to tidal waters. Occasional to frequent low salinity conditions were inferred from close proximity of freshwater sprinkler systems and a paved parking lot just above and adjacent to the location where *A. nodosum* was found; however, no direct salinity measurements of pore water at the site were performed. The mean wet weight (± 1 SE) per plant or plant fragment was 260.5 ± 65.1 g (n = 144; range, 0.2 to 8110 g). Of these, 39 specimens had wet weights that ranged from 229 to 8110 g.

It appears that the *A. nodosum* found in Redwood City had colonized and was growing *in situ* based on two criteria. First, the 174 *Ascophyllum* plants and plant fragments appeared healthy and showed no outward signs of stress (i.e. discoloration or decomposition). Algae require inorganic carbon, water, light, and various mineral ions for photosynthesis and growth; severely stressed or nutrient-deprived fucoid algal thalli exhibit conspicuous discoloration in the form of yellowing and reddening, usually leading to death of the plant (Lobban and Harrison 1994). Had the alga been unable to tolerate the Redwood City habitat, various degrees of stress and decomposition would have been expected, but no such signs were observed either at the time of initial discovery or 10 weeks later when eradication efforts were initiated. Second, the plants were all of a single morphology, the free-living *A. nodosum* ecad *mackayi*. No transitional morphologies or range of growth forms were found.

Such occurrences have three possible explanations: 1) all the algae arrived to the site as ecad *mackayi*; 2) the algae were present at the site long enough to undergo transformation from other morphologies; or 3) the plants resulted from the invasion by a single plant that proliferated and/or transformed from one morphology to another. The habitat and physical characteristics of the alga found in Redwood City were consistent with those described for *A. nodosum* ecad *mackayi* by Gibb (1957) and South and Hill (1970), suggesting that the location is habitable and has the potential to promote phenotypic expression of ecad *mackayi*. The putative invasion pathway for *A. nodosum* to San Francisco Bay is discarded seafood packing material (Miller 1969) or bait worm packing material (Cohen and Carlton 1995, Lau 1995, Carlton and Cohen 1998), both originating in New England. The presence of floating bunches of *A. nodosum* has been noted in San Francisco Bay, but colonization has never been observed (Silva 1979, Josselyn and West 1985). Handfuls of *A. nodosum* discarded by fishermen on the San Francisco Bay shoreline typically exhibit discoloration and decomposition and also are usually *A. nodosum* ecad *scorpioides* (A. Chang, personal observation).

Given the predominance of the typical holdfast-bearing *A. nodosum* in New England and its dominance as seafood packing material, repeated or even a single large inoculation of the much rarer free-living ecad *mackayi* seems highly unlikely. The absence of either transitional morphologies or harvest marks (thalli severed from the holdfast) and lack of clear decomposition or stress argue for the alga's longer term undetected presence. In the event that *A. nodosum* was introduced to San Francisco Bay as a single plant,

TABLE 1. Taxa found in samples of *Ascophyllum nodosum* ecad *mackayi* collected from an intertidal habitat in the southwestern San Francisco Bay (Redwood City, California, USA).

Taxon	Identification
Chlorophyta	
Ulva sp.	No ID
Porifera	
Haliclona sp.	N
Annelida	
Polychaeta	
Spirorbids (multiple spp.)	No ID
Mollusca	
Gastropoda	
Ilyanassa obsoleta	E
Littorina saxatilis	E
Urosalpinx cinerea	E
Haminoea vesicula	N
Bivalvia	
Geukensia demissa	E
Musculista senhousia	E
Mytilus sp.	No ID
Arthropoda	
Crustacea	
Balanus glandula	N
Balanus improvisus	E
Hemigrapsus oregonensis	N
Gammarid amphipods (multiple spp.)	No ID
Arthropoda:	
Crustacea	
Sphaeroma quoyanum	E
Sphaeromatid isopods (1–2 spp.)	No ID
Bryozoa	
Bugula neritina	E
Cryptosula pallasiana	E
Bowerbankia sp.	C
Chordata	
Tunicata	
Botrylloides sp.	C

C, cryptogenic; E, exotic; ID, identification; N, native.

the sheer number of plants detected suggests that the alga was present for a long enough time to proliferate and then grow to the sizes found.

Ascophyllum nodosum bait and seafood packing material has been considered a possible vector for nonindigenous species introductions for over 30 years (Miller 1969, Carlton 1979). Both the European green crab, *Carcinus maenas* Linnaeus 1758, and the rough periwinkle, *Littorina saxatilis* (Olivi 1792), are thought to have been introduced to San Francisco Bay with seaweed packing materials in recent years (Cohen and Carlton 1995, Carlton and Cohen 1998). *Ascophyllum* mats from Redwood City contained a mixture of native and exotic taxa (Table 1). Because all the exotic species listed have been recorded in San Francisco Bay previously, none is new to the Bay; however, whether any new individuals (including possible new genetic stocks) were actually introduced with this seaweed could not be deduced. Because *A. nodosum* ecad *mackayi* lacks holdfasts, it is only held in place by means of tangling around rooted vegetation or adherence via suction and friction to hard substrates. Free-living forms of *A. nodosum* can be easily dislodged by surging water and float to other locations. This situation poses a threat of potential colonization by the alga and its inhabitants to places elsewhere in San Francisco Bay and on the outer Pacific coast.

Based on the limited invasion patch size, the threat of rafting of the alga and associated species, and the broad environmental tolerances and thus potential for large scale geographic spread of *A. nodosum*, we decided to manually remove the seaweed from the environment. Systematic manual removal efforts were carried out from 19 November 2002 until 21 November 2002 with permission from the California Department of Fish and Game and the Port of Redwood City, which owns and leases the shoreline on which the *Ascophyllum* was found. An area of intertidal habitat encompassing the site was divided into 10 adjacent 1×30 m transects running parallel to the water's edge. Each transect was searched systematically, and all plants and plant fragments of *A. nodosum* were measured (maximum length $\times$ perpendicular dimension). Approximately 174 individual plants and fragments were bagged and their locations recorded. Plants and fragments were taken back to the laboratory and weighed. In total, 37.6 kg (approximately 0.2 m^3) of *A. nodosum* were removed from the site. The algae were examined, photographed, doubled bagged in plastic, and disposed of in a landfill. After initial eradication efforts, the site has been monitored at 2- to 3-month intervals and all remaining seaweed removed. *Ascophyllum nodosum* has not been detected at the Redwood City site since December 2002, suggesting a successful local eradication of this species. Monitoring of the site will continue to ascertain the long-term success of eradication.

Eradication of nonindigenous species is likely impossible in most instances. However, Myers et al. (2000) described the feasibility and cost-to-benefit considerations of undertaking eradication programs and indicated six requirements for successful eradication programs:

1. The resources must be sufficient to bring eradication to its conclusion.
2. The lines of authority must be clear with respect to how an eradication is carried out and who will accomplish the task.
3. The biology of the target organism must be susceptible to control procedures.
4. Reinvasion must be prevented.
5. Target organism must be detectable at low levels.
6. Eradication may require restoration of native community.

In the case of *A. nodosum*, selective manual removal of the seaweed was agreed on by the participating agencies as a promising, cost-effective, and environmentally sensitive method of eradication. The total cost of this eradication effort, including the ongoing site monitoring program, has been approximately $4680 (U.S. dollars). This figure includes 20 person-hours for planning and logistics, 82 person-hours for removal and monitoring, and the cost of travel and supplies. Requirement 4 from Meyers et al. (2000) has not yet

been addressed, because the commercial transport of *A. nodosum* by the seafood and bait worm industries and subsequent disposal of this alga is currently unregulated. As such, we suspect that reinvasion is still possible if the alga reaches appropriate habitats. In the absence of stricter guidelines for shipment and disposal of *A. nodosum*, we anticipate future invasions by this species and its associated biota in other coastal bays on the Pacific coast of North America as well as other locations in the world.

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