Aquatic Invasions (2009) Volume 4, Issue 3: 429-434
DOI 10.3391/ai.2009.4.3.1

Research article

Northern range expansion of the Asian kelp *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyceae) in western North America

Chela J. Zabin*, Gail V. Ashton, Christopher W. Brown and Gregory M. Ruiz
Smithsonian Environmental Research Center, 3152 Paradise Drive, Tiburon, California, USA
E-mail: zabinc@si.edu (CJZ), ashtong@si.edu (GVA), browncw@si.edu (CWB), ruizg@si.edu (GMR)
**Corresponding author*

Received 24 May 2009; accepted in revised form 2 September 2009; published online 7 September 2009

Abstract

The kelp *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyceae), a native of Japan, northern China, and Korea, is now established at multiple locations throughout the world, including the west coast of the United States and Mexico. In 2000, *U. pinnatifida* was first reported in the United States from Los Angeles Harbor, California. Within a year, it had also been found 500 km to the north, in Monterey Harbor, California. In 2002, this alga was reported from Ensenada, Mexico to Monterey, California, and no subsequent spread has been reported since this time. In May 2009, we discovered *U. pinnatifida* to the north, at two marinas in San Francisco Bay and the outer coastal harbor at Pillar Point, San Mateo County. All observed individuals were removed and measured. Based on size and reproductive status, it appears that multiple cohorts were present. Transfer on the hulls of recreational boats is suggested as the source of this recent range expansion in California. Given the large flux of both recreational and commercial boat traffic in San Francisco Bay, this may become an important source for further spread both along the coast and to other biogeographic regions.

Key words: invasive algae, range expansion, San Francisco Bay, recreational craft, marinas

Introduction

The kelp *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyceae), a native of Japan, northern China, and Korea, is now established in multiple locations throughout the world, including the Atlantic Coast of Europe, the Mediterranean Sea, New Zealand, Tasmania, Argentina, and the west coast of the United States and Mexico (Silva et al. 2002; Aguilar-Rosas et al. 2004). As suggested by its distribution, *U. pinnatifida* can thrive in a wide range of physical conditions. A substrate generalist, it is common (but not limited) to sheltered waters, especially harbors. The species can tolerate temperatures from 0-27°C (Funahashi 1973; Hay 1990) and salinities from oceanic conditions to as low as 20 psu (Wallentinus 1999).

This alga has a biphasic life cycle, alternating between a large diploid sporophyte generation (typically up to 1.5 m length in the wild, but as large as 3 m in aquaculture) and a microscopic haploid gametophyte generation. In its native range, sporophytes grow rapidly in the winter, mature in the late spring, and disintegrate in the summer when temperatures reach 14-23°C, with peak release 17-22°C (Saito 1975). While this pattern is seen in some of its non-native range, it appears to differ in other regions. In Brittany and New Zealand, generations overlap, with the large sporophyte stage present throughout the year (Hay and Villouta 1993; Castric-Fey et al. 1999). In Monterey, California there are seasonal pulses, with some sporophytes present all year (S. Lonhart, pers. comm.). In locations such as Southern California, where the sporophyte stage dies back in the summer, native algae may have a chance to grow and potentially out-compete *U. pinnatifida* via shading (Thornber et al. 2004). In areas where large individuals are present year round, concerns for the potential impacts on native algae and ecosystems are greater, particularly in more natural settings.

Some of the spread of *U. pinnatifida* around the world can be attributed to accidental transfer associated with aquaculture, but transfer via boat fouling is implicated in many of these invasions (Forrest et al. 2000; Silva et al. 2002; Thornber et al. 2004). The alga was first reported on the west coast of the United States in 2000 from Los Angeles Harbor (Silva et al. 2002). It was subsequently reported from Catalina Island, 35 km offshore from Los Angeles, and from various harbors north to Santa Barbara. Within a year, it had been found 500 km to the north of Los Angeles, in Monterey Harbor, and by 2002 was reported to have a range from Ensenada, Mexico to Monterey (Silva et al. 2002; Aguilar-Rosas et al. 2004). Within this region, the alga is found mainly in harbors and marinas, but it has spread into a kelp forest at Catalina Island to depths of 45 feet (J. Smith, pers. comm.) While no further northward spread has been reported in the past seven years, environmental conditions appear suitable for establishment of *U. pinnatifida* as far north as British Columbia and southeast Alaska.

In May 2009, we discovered numerous large sporophytes at a marina in San Francisco Bay. Following this discovery, we conducted rapid visual surveys for *U. pinnatifida* at six additional marinas within the Bay and two boat harbors along the surrounding outer coast (one to the north and one to the south). Here, we (a) report the 170 km northward range expansion of *U. pinnatifida* for western North America, (b) characterize the newly observed populations, and (c) consider some implications for further coastwise spread.

Material and Methods

We discovered the first individuals in San Francisco Marina Yacht Harbor (SF Marina) on 8 May 2009, during a dockside survey of bio-fouling organisms on recreational vessels in San Francisco Bay and nearby harbors. Following the discovery of *U. pinnatifida*, two people walked the entire marina, examining every boat at berth and looking along the edges and ends of each berth for *U. pinnatifida*. Mature individuals of *U. pinnatifida* are quite distinct from other macroalgae native to San Francisco Bay. Smaller individuals were identified using color, shape and the presence of a midrib.

From 14-22 May 2009, we surveyed 6 additional marinas within San Francisco Bay including Pier 39 and South Beach Harbor in San Francisco; Presidio Yacht Harbor and Clipper Yacht Harbor, north of San Francisco in the city of Sausalito; Treasure Island and Berkeley Marina, in the bay and east of San Francisco (Figure 1, Annex 1). These marinas were selected for our initial assessment due to their proximity to SF Marina, their active sailing communities, and the similarity of salinity and other physical conditions to that of the SF Marina.

In this same time period, we also surveyed two harbors along the outer coast, north and south of San Francisco Bay. Bodega Harbor (Spud Point), Sonoma County, is the nearest harbor to the north along the coast (70 km from the mouth of SF Bay), and Pillar Point Harbor in Half Moon Bay, San Mateo County, is 35 km to the south (Figure 1). We selected these locations because they are the harbors outside of the bay most frequently visited by San Francisco boaters (Davidson et al. 2008).

During our surveys, we walked the entire marina, examining algal growth visible from above the waterline on boats and maritime structures specifically to detect *U. pinnatifida*. When the alga was encountered, we removed all observed individuals, measured length, and recorded reproductive status. While smaller individuals would certainly go unnoticed with this method, particularly if they were growing among other algal species, our goal was to carry out an initial rapid assessment of extent of the invasion in San Francisco Bay and nearby harbors.

Results

We detected *U. pinnatifida* at 3 of the 9 sites surveyed in northern California (Figure 1, Annex 1). The alga was observed at two marina sites in San Francisco Bay, including SF Marina and South Beach Marina. In addition, we found *U. pinnatifida* at Pillar Point Harbor, Half Moon Bay, on the outer coast between San Francisco Bay and Monterey Bay (Figure 1).

Eighty-three individuals and 6 holdfasts (~30 kg wet weight) were found along a portion of a single floating dock (or pontoon) approximately 100 m in length in the East Harbor of SF Marina (Figure 2). Nearly a dozen of these were attached to the hulls of motor boats, and the rest were attached to floating docks, as well as on fixed pilings, and submerged tires and ropes. Sizes ranged from 20 to 220 cm in total length, with

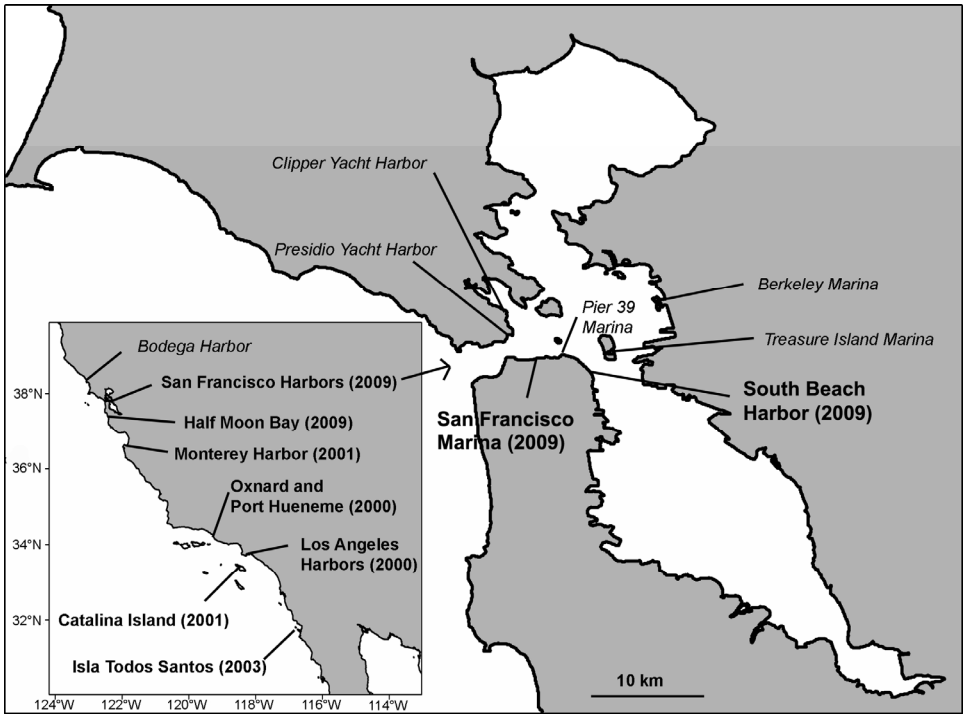

Figure 1. Marinas in San Francisco Bay searched for *Undaria pinnatifida*. The alga was present at the locations in bold face; year of first report indicated in parenthesis. Inset: Reports of *U. pinnatifida* along the US west coast and location of the two coastal harbors we surveyed. See Annex for details

Figure 2. *Undaria pinnatifida* from the East Harbor of SF Marina. Photograph by C.J. Zabin

a mean of 102 cm. All but 14 of the individuals were reproductive. Larger thalli were showing signs of dis-integration. This population had a high density center focused around 40 berths about mid-way down the dock, and edges past which we did not find any individuals.

Nine large, reproductive thalli were also detected on two floating docks at South Beach Marina. All were found in a small area encompassing a guest dock and one that berthed large motor boats. All individuals were reproductive; five showed signs of disintegration. Mean size was 74 cm in total length, and individuals ranged from 40 to 130 cm. Total wet weight of all algae collected was 4 kg.

Eighteen thalli were found at Pillar Point Harbor along two adjacent floating docks, on six boats, and the docks themselves. These included several large, reproductive individuals, but were generally smaller than those found in SF Bay. Mean size was 52 cm in total length; sizes ranged from 10 to 177 cm. Total wet weight of all algae collected was 1.8 kg.

Discussion

The discovery of *Undaria pinnatifida* in Half Moon Bay and at two marinas in San Francisco Bay represents a significant northern range expansion, following 7 years after its detection in Monterey Bay. *Undaria pinnatifida* is one of many non-native species moving north along the west coast of North America after initial invasion in California (Cohen et al. 1998; Wonham and Carlton 2005; Ruiz et al. 2006). It appears that the coastal spread of these species is often driven by human-mediated transfer, especially associated with vessels. For northern localities, such as Alaska, this is likely to increase in response to climate change and increases in vessel traffic and other anthropogenic sources of propagule supply (Ruiz and Hewitt 2009).

Life history information suggests that *U. pinnatifida* could spread naturally from a source population at the scales of tens of meters. However, at numerous locations, actual spread has occurred at the scale of hundreds of meters, suggesting an anthropogenic vector (Forrest et al. 2000). In California, the history of spread and our newly detected range expansion suggest vessels, and especially small boats, as the mechanism of introduction.

SF Marina comprises two basins, each of which has 343 slips. It houses pleasure craft almost exclusively, although there are some smaller commercial fishing boats. South Beach Harbor has 700 slips and a 200 m guest dock for commercial and recreational craft. These marinas do not keep records on the total number of visiting boats or where they come from (Larry White and James White, pers. comm.).

While our study focused on the arrival of *U. pinnatifida* to San Francisco Bay, history suggests this is an important hub for secondary spread. The role of San Francisco Bay as a significant source for secondary transfers of marine invaders has been hypothesized for some time (Cohen and Carlton 1995). Indeed, the striking similarity between the non-native fauna of San Francisco Bay and that of Elkhorn Slough, approximately 150 km to the south, suggests San Francisco Bay was a significant source of species transfers via vessel traffic (Wasson et al. 2001).

Certainly an increased range of any non-native species increases transfer opportunities, but San Francisco Bay may be especially potent in this regard, due to the magnitude of vessel traffic and connectivity to other regions. For recreational vessels, a boater survey in 2007 found that 14.5% of San Francisco Bay-based boaters had left the Bay within the previous 12 months (Davidson et al. 2008), and there are some 150,000 boats registered in California to owners who live in the counties along the Bay shoreline (California Boater Facilities Needs Assessment 2000). San Francisco is also a stop for many recreational vessel arrivals from foreign ports that are traveling the coast and are required to fill out customs paperwork there. Thus, the volume of small-boat traffic transiting through the Bay may be high. Perhaps not surprisingly, Half Moon Bay and Monterey Bay (both infested with *U. pinnatifida*) are popular destinations for local boaters from San Francisco Bay (Davidson et al. 2008). San Francisco area boaters also reported frequent visits to locations in a national marine sanctuary and national park: two open coast locations, Muir Beach and the Farallon Islands, and a wave-protected estuary, Drakes Bay (Davidson et al. 2008). Pillar Point Harbor, while considerably smaller than the two San Francisco marinas, had more than 1000 visiting boats in 2007, including many commercial fishing boats arriving from coastal ports in Northern California (Zabin et al., unpublished data).

In addition to its transiting recreational vessels, San Francisco Bay is also an important commercial port system. An estimated annual average of 3200 commercial vessels arrive to to high salinity (> 20 psu) ports within the San Francisco Bay (2006-2008; NBIC 2009), where environmental conditions are within the reported tolerance of *U. pinnatifida*.

Thus, a large population of vessels exists in San Francisco Bay, and the hulls of both recreational and commercial vessels are potentially available for colonization by the microscopic gametophyte stage of this alga, facilitating spread coastwise and to other global regions. Despite the potential, the dynamics (and risk) of such colonization and spread are poorly understood.

The work reported here represents an initial survey for *U. pinnatifida* in San Francisco Bay and environs. The size of individuals found in the Bay suggests that this alga had been present for at least two months prior to our discovery, and the reproductive status suggests that Bay marinas have already received an inoculation of spores. Additional surveys of marinas in San Francisco Bay and harbors between Monterey

and San Francisco are planned. These surveys will include in-water examinations of floating structures for smaller individuals that may have been missed by this initial survey. Surveys later in the year are also being planned.

We are now exploring potential management options at these sites to limit further expansion. Among the difficulties for managing *U. pinnatifida* is the tiny gametophyte stage, which presumably can attach to boats and spread undetected to additional locations. Advancing molecular detection methods for these microscopic life stages may be a critical step, to screen both marinas and individual boats for the presence of this stage.

Acknowledgements

We thank Steve Lonhart for helpful discussions and the harbor masters at the above marinas for their interest and co-operation. This invader was discovered in the course of a project examining the potential role of recreational and fishing vessels in the spread of invasive species via hull fouling, supported by NOAA and the Pacific States Marine Fisheries Commission, grant #NA08OAR4170927. We also thank Kathy Ann Miller and Frederic Mineur for their helpful suggestions on the manuscript.

References

Aguilar-Rosas R, Aguilar-Rosas LE, Ávila-Serrano G, Marcos-Ramírez R (2004) First record of *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyta) on the Pacific coast of Mexico. Botanica Marina 47: 255-258 doi:10.1515/BOT.2004.028

California Boater Facilities Needs Assessment (2000) Volume 2, Regional boaters and boating facilities. Sacramento, California, 132 pp

Castric-Fey A, Beaupoil C, Bouchain J, Pradier E, L'Hardy-Halos M. Th (1999) The introduced alga *Undaria pinnatifida* (Laminariales, Alariaceae) in the rocky shore ecosystem of the St. Malo area: growth rate and longevity of the sporophyte. Botanica Marina 42: 83-96 doi:10.1515/BOT.1999.011

Cohen AN, Carlton JT (1995) Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. Report submitted to US Fish & Wildlife Service, 246 pp

Cohen AN, Mills C, Berry H, Wonham M, Bingham B, Brookheim B, Carlton J, Chapman J, Cordell J, Harris L, Klinger T, Kohn A, Lambert CC, Lambert G, Li K, Secord D, Toft J (1998) Puget Sound expedition: a rapid assessment survey of non-indigenous species in the shallow waters of Puget Sound. Report submitted to the Washington State Department of Natural Resources, 37 pp

Davidson I, Zabin CJ, Chang A, Sytsma M, Ruiz G (2008) Characterizing the risk of species transfers on recreational boats in marine systems via hull fouling: a pilot study. Report submitted to US Fish & Wildlife Service, 38 pp

Forrest BM, Brown SN, Taylor MD, Hurd CL, Hay CH (2000) The role of natural dispersal mechanisms in the spread of *Undaria pinnatifida* (Laminariales, Phaeophyceae). Phycologia 39: 547-553

Funahashi S (1973) Distribution of marine algae in the Japan Sea, with reference to the phytogeographical locations of Vladivostok and the Noto Peninsula districts. Journal of the Faculty of Science, Hokkaido University Ser V (Botany) 10:1-31

Hay CH (1990) The dispersal of sporophytes of *Undaria pinnatifida* by coastal shipping in New Zealand, and implications for further dispersal of *Undaria* in France. British Phycological Journal 25:304-313 doi:10.1080/00071619000650331

Hay CH, Villouta E (1993) Seasonality of the adventive Asian kelp *Undaria pinnatifida* in New Zealand. Botanica Marina 36: 461-476

NBIC (2009) National Ballast Information Clearinghouse, http://invasions.si.edu/nbic/ (Accessed on May 20 2009)

Ruiz GM, Huber T, Larson K, McCann L, Steves B, Fofonoff P, Hines AH (2006) Biological invasions in Alaska's coastal marine ecosystems: establishing a baseline. Final report to Prince William Sound Regional Citizens' Advisory Council and U.S. Fish & Wildlife Service 112 pp

Ruiz GM, CL Hewitt CL (2009) Latitudinal patterns of biological invasions in marine ecosystems: a polar perspective. In: Krupnik I, Lang MA, Miller SE (eds), Smithsonian at the Poles: Contributions to International Polar Year Science, Smithsonian Institution Scholarly Press, Washington, pp 347-358

Saito Y (1975) *Undaria*. In Tokida J, Hirose H (eds), Advance in Phycology in Japan, The Hague, Junk, pp 304-319

Silva PC, Woodfield RA, Cohen AN, Harris LH, Goddard JHR (2002) First report of the Asian kelp *Undaria pinnatifida* in the northeastern Pacific Ocean. Biological Invasions 4: 333-338 doi:10.1023/A:1020991726710

Thornber CS, Kinlan BP, Graham MH, Stachowicz JJ (2004) Population ecology of the invasive kelp *Undaria pinnatifida* in California: environmental and biological controls on demography. Marine Ecology Progress Series 268: 69-80 doi:10.3354/meps268069

Wallentinus I (1999) *Undaria pinnatifida* (Harvey) Suringar. In: Gollash S Minchin D Rosenthal H Voight M (eds) Case Histories on Introduced Species: Their General Biology, Distribution, Range Expansion and Impact, Department of Fishery Biology, Institute for Marine Sciences, University of Kiel, Germany, pp 13-19

Wasson K, Zabin CJ, Bedinger L, Diaz MC, Pearse JS (2001) Biological invasions of estuaries without international shipping: the importance of intraregional transport. Biological Conservation 102: 143-153 doi:10.1016/S0006-3207(01)00098-2

Wonham M, Carlton JT (2005) Cool-temperate marine invasions at local and regional scales: The Northeast Pacific Ocean as a model system. Biological Invasions 7(3): 369-392 doi:10.1007/s10530-004-2581-7

Annex 1
Records of the Asia kelp *Undaria pinnatifida* along the West Coast of North America

Location	Geographic coordinates		Survey date(s)	Species present (Yes/No)	Reference
	Latitude, N	Longitude, W			
San Francisco Marina, SF	37°48'26"	122°26'04"	5/8/2009 and 5/18/2009	Yes	Present study
South Beach Harbor, SF	37°46'52"	122°23'09"	5/15/2009	Yes	Present study
Pier 39 Marina, SF	37°48'33"	122°24'35"	5/15/2009	No	Present study
Clipper Yacht Harbor, Sausalito	37°52'09"	122°29'50"	5/14/2009	No	Present study
Presidio Yacht Harbor, Sausalito	37°49'55"	122°28'29"	5/14/2009	No	Present study
Berkeley Marina, Berkeley	37°52'00"	122°18'59"	5/16/2009 and 5/17/2009	No	Present study
Treasure Island, SF	37°48'53"	122°22'11"	5/26/2009	No	Present study
Spud Point, Bodega Bay	38°19'43"	123°03'27"	5/19/2009	No	Present study
Pillar Point, Half Moon Bay	37°30'08"	122°29'06"	5/22/2009	Yes	Present study
Monterey Harbor	36°36'11"	121°53'28"	August 2001	Yes	Silva et al. 2002
Oxnard and Point Hueneme	34°10'16"	118°15'13"	June and November 2000	Yes	Silva et al. 2002
Los Angeles Harbors	33°43'31"	118°15'13"	March, May, June 2000	Yes	Silva et al. 2002
Catalina Island	33°21'43"	118°18'36"	June 2001	Yes	Silva et al. 2002
Todos Santos, Baja California	31°48'05"	116°47'13"	9/28/2003	Yes	Aguilar-Rosas et al. 2004