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*Invasion note*

# First report of the Asian kelp *Undaria pinnatifida* in the northeastern Pacific Ocean

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**Abstract**

The Asian kelp *Undaria pinnatifida* was discovered in southern California in the spring of 2000, and by the summer of 2001 had been collected at several California sites from Los Angeles to Long Beach Harbors and Catalina Island as far north as Monterey Harbor. From its native range in the northwestern Pacific, *Undaria* has now been introduced to the northeastern and southwestern Atlantic and the southwestern and northeastern Pacific, through a combination of intentional transport for cultivation, accidental transport with oysters, as fouling on vessel hulls, and possibly other means. In the northeastern Pacific, water temperatures are suitable for its establishment from at least Baja California to British Columbia, where it is likely to grow well in sheltered and partially sheltered waters.

The discovery of several populations of the large Asian kelp *Undaria pinnatifida* (Harvey) Suringar (in the brown algal order Laminariales) in southern California marks the latest stage in the anthropogenic global spread of this species, which began in the 1970s. *Undaria* is native to Japan, northern China and Korea, where it is cultivated and sold commercially for food. It has become established in the Mediterranean Sea, Atlantic Europe, New Zealand, Tasmania and Argentina.

The first California specimens of *Undaria* were discovered in Los Angeles Harbor in March 2000. By August 2001, several additional harbor populations had been found on floating piers or in shallow water as far as Monterey Bay, 500 km to the north, and at depths of up to 25 m in a bay on Catalina Island, about 35 km offshore of Los Angeles (Figure 1, Table 1). In Japan, *U. pinnatifida* exhibits considerable morphological variability correlated with latitude, and the form in southern California matches that which is found in southern Japan (Okamura 1915, p. 267) (Figure 2).

The maximum length of *Undaria* fronds in nature is usually about 1.5 m, but fronds as long as 3 m have been recorded in cultivation (Perez et al. 1984). These fronds, comprising a holdfast, stipe (stem) and blade, are diploid sporophytes. Haploid spores are formed following meiotic division of the initial diploid nucleus in unilocular sporangia that are grouped in fertile areas called sori. Kelps are grouped into families primarily on the basis of the position of sori. In the Laminariaceae, they are produced on the blade, while in the Alariaceae they are restricted to special structures called sporophylls. In *Alaria* and *Pterygophora* on the California coast, the sporophylls are flattened outgrowths arising from the stipe proximal to the blade. In *U. pinnatifida*, by contrast, the sporophylls are ruffled wings along both sides of the flattened lower portion of the stipe. The generic name is derived

*Figure 1.* The kelp *U. pinnatifida* growing on the side of a floating dock in Santa Barbara Harbor, 24 April 2001.


*Figure 2. Undaria pinnatifida* collected on a spill boom in Los Angeles Harbor, March 2000; specimen deposited in the Jepson Herbarium, University of California, Berkeley.

*Table 1. Undaria pinnatifida* in California.

| Site | Comments (source of record) |
|---|---|
| Los Angeles Harbor (Cabrillo Beach) | March 2000, on a floating pier and floating boom (R.A. Woodfield); abundant mature sporophytes in June 2000, senescing in August (L.H. Harris, A.N. Cohen); not observed on the pier in the 1990s (L.H. Harris). |
| Long Beach Inner Harbor | May 2000, on steep, subtidal channel banks in dense stand of *Ulva* (R. Woodfield). |
| Channel Islands Harbor, Oxnard | June 2000, a few mature sporophytes on floating marina piers near mouth of harbor, none observed in August 2000 (L.H. Harris, A.N. Cohen); April 2001, a few senescent sporophytes on eastern side of harbor (J.H.R. Goddard). |
| Port Hueneme | November 2000, at several sites mainly toward back of harbor (E. Landrau, C. Roberts, M. Foster). |
| Santa Barbara Harbor | April 2001, thriving population on floating piers and concrete pilings in a few slips that house transient boats, including both mature and senescent sporophytes (J.H.R. Goddard, P. Dyrynda); 190 kg of *Undaria* (wet weight) removed in May 2001 (J.H.R. Goddard). |
| Catalina Island (Button Shell Cove) | June 2001, on *Chaetopterus* tubes on sand bottom at 20–25 m and on tires at 6 m (J. Engle, K.A. Miller). |
| Monterey Harbor | August 2001, on floating docks (L. Hunt). |

from *unda*, the Latin word for wave, referring to the ruffled wing.

After the laterally biflagellate, haploid spores are released, they typically swim for up to 5–6 h before settling on a firm substrate, where they develop directly into microscopic, filamentous male and female gametophytes (Kanda 1936; Hay and Luckens 1987). Biflagellate male gametes are released and fertilize the eggs retained in the female gametophytes, which then develop *in situ* into embryonic sporophytes. Growth boundaries reported in various studies range from 3 to 20 °C for sporophytes and 10 to 24 °C for gametophytes (Sanderson 1990; Wallentinus 1999; Sinner et al. 2000), though *Undaria* sporophytes have been reported in habitats with a temperature range of 0–27 °C (Hay 1990; Castric-Fey et al. 1999). *Undaria* occurs mainly in salinities above 27 psu, but occasionally down to around 20 psu (Wallentinus 1999).

*Undaria*'s first appearance outside of the northwestern Pacific was in the Etang de Thau, a lagoon on the Mediterranean coast of France, in 1971, having apparently been imported accidentally with Pacific oysters (*Crassostrea gigas*), which are cultivated in the lagoon. *Undaria* subsequently spread along the south coast of France, to two sites in Italy, and to several Atlantic coast sites from northwestern Spain to The Netherlands and southern England, through a combination of intentional transport for cultivation and accidental transport with oysters or as fouling on vessel hulls, and possibly by other means. It was discovered in New Zealand in 1987, where it has spread to numerous sites on North, South and Stewart islands, in Tasmania in 1988, in Golfo Nuevo in Argentina in 1992, and in Port Phillip Bay in southeastern Australia in 1996 (details provided in Table 2).

From the descriptions of *Undaria*'s various introductions together with our own observations in southern California, some patterns in its distributional ecology and reproduction can be discerned. First, sporophytes grow on any available firm substrate, including rocks, wood, concrete, metal, plastic, glass, rubber and on or over various organisms (including coralline algae, seagrass blades, chaetopterid and serpulid worm tubes, bivalves, barnacles and ascidians), and are often found just below the waterline attached to breakwaters, seawalls, buoys, ropes, floating piers or the hulls of vessels (Hay and Luckens 1987; Sanderson 1990; Hay 1990; Piriz and Casas 1994; Lewis 1999; Sinner et al. 2000; K.A. Miller pers. comm. 2001). Second, they prefer sites that are at least somewhat protected, though they can grow in open coast sites (Hay and Villouta 1993; Floc'h et al. 1996; Hay and Luckens 1987). Third, their growth is not prevented by organic pollution. At several sites, colonized areas are close to urban sewage emissions (Curiel et al. 1994; Castric-Fey et al. 1999; Talman et al. 1999; Cecere et al. 2000). Fourth, in some areas of introduction, seasonality is similar to that observed in Japan, that is, sporophytes begin rapid growth in winter, mature in late spring, and disintegrate and disappear in summer when water temperatures reach 20–25 °C (Hay and Villouta 1993). In other sites, including the Brittany Coast of France and in New Zealand, there are two or more generations per year, with sporophytes present and spore release occurring throughout all or nearly all of the year (Hay and Villouta 1993; Castric-Fey et al. 1999).

Water temperatures along the Pacific Coast of the United States are favorable for the establishment of *U. pinnatifida* from at least Baja California to British Columbia. Sheltered and partially sheltered regions including the Southern California Bight, Monterey Bay, the more oceanic parts of San Francisco Bay, Tomales and Humboldt Bays, and Puget Sound would seem to offer excellent growing conditions. Much of the intervening coast may be too exposed, although there are reports of populations on exposed shores in Japan, New Zealand and Tasmania (Hay 1990; Hay and Villouta 1993).

Once established, the eradication or control of populations of *Undaria* is probably impossible. A single frond releases an astronomical number of zoospores, which appear to settle randomly. Probably all fertilized eggs develop into embryonic sporophytes. If the latter manage to survive grazers, their very rapid growth ensures continued survival unless the spores settle intertidally, causing the frond to be damaged by sunlight when it is exposed by low tides. Eradication efforts based on manual removal have been unsuccessful, and the eradication of an established population through the use of biocides would appear to be impossible except perhaps in an enclosed basin (Burridge and Gorski 1998; Curiel et al. 1998; Sinner et al. 2000).

*Undaria* has likely been encountered by anyone who has been served a cup of miso soup in a Japanese restaurant. Thin green pieces of *wakame* (the Japanese name for *Undaria*) are traditionally floated on the soup, to which they impart flavor and texture. For centuries, Japanese have harvested wakame from nature, preserved it in various ways, and used it as food. Recipes

*Table 2.* Global spread of *Undaria pinnatifida*.

| Region | Sites and dates of first records |
|---|---|
| Northwestern Pacific | Native range includes eastern China, Sea of Japan (Japan, Korea, southeastern Russia), east coast of Japan from southern Hokkaido to southern Honshu, and Okhotsk Sea (Saito 1975; Floc'h et al. 1991; Wallentinus 1999; Cecere et al. 2000). Cultivated in China in areas with sparse natural populations since the 1930s, and in Taiwan since 1981 (Zhang et al. 1984; Wallentinus 1999). |
| Northeastern Atlantic | Mediterranean: In Etang de Thau, a lagoon in southern France, in 1971 (Perez et al. 1981), and spread eastward to Port Vendres, near Spain, by 1988 (Hay 1990). In Venice Lagoon in northern Italy in 1992 and in Mar Picolo, an enclosed basin in Taranto in southern Italy, in 1999 [not at Bari as reported in Wallentinus 1999 – I. Wallentinus, pers. comm. 2002] (Curiel et al. 1994; Cecere et al. 2000).<br>Atlantic: Transported from Etang de Thau to Brittany coast of France for cultivation in 1983 (Perez et al. 1984), established in the wild by 1987 and found at sites from Île de Groix to Granville (Floc'h et al. 1991, 1996). In northwestern Spain in Galicia by 1988, where it occurred in the Arousa and Betanzos estuaries, and in Asturias at Gijón by 1995 (Salinas et al. 1996; Pérez-Cirera et al. 1997). Discovered on marina floats in Solent region of southern England in 1994–1998 at Hamble Estuary, Portsmouth Harbor, Chichester Harbor and Cowes on the Isle of Wight, in Devon in 1996, in Sussex in 1997, and at Jersey in the Channel Islands (Fletcher and Manfredi 1995; Fletcher and Farrell 1999). At Calais in northeastern France in 1998, and in Belgium and the Oosterschelde region of the Netherlands in 1999 (Wallentinus 1999). |
| Southwestern Pacific | In New Zealand at Wellington on North Island and at Timaru on South Island in 1987, and at Paterson Inlet on Stewart Island in 1997; by 2000 established at numerous sites on the east and south coast of North Island from Gisborne to Porirua, and on the north and east coast of South Island from Golden Bay to Bluff (Hay and Luckens 1987; Hay 1990; Forrest et al. 2000). In southeastern Tasmania near Triabunna in 1988 (Sanderson 1990; Hay 1990); found at several sites from Coles Bay to D'Entrescasteaux Channel, a distance of about 150 km, by 1999 (Lewis 1999). In Port Phillip Bay in southeastern Australia in 1996 (Campbell et al. 1999). |
| Southwestern Atlantic | In Golfo Nuevo in Argentina in 1992 (Piriz and Casas 1994; Casas and Piriz 1996). |
| Northeastern Pacific | In California from Long Beach Harbor to Port Hueneme in 2000; on Catalina Island and north to Monterey Harbor in 2001 (this paper). |

that include wakame may be found in various specialty cookbooks (e.g. Madlener 1977; Arasaki and Arasaki 1983). Wakame is found in abundance on partly protected rocky coasts all along the Sea of Japan and from southern Hokkaido to southern Honshu on Japan's east coast, where it grows in the lowest intertidal zone and subtidally to a depth of about 15 m (Saito 1975). To prevent the exhaustion of the natural resource and to improve productivity, various methods of cultivation have been developed in Japan since 1952. In general, the thalli are induced to grow on suspended ropes or nets in the field or in tanks. The cultivation of wakame was successfully exported to China in areas with relatively sparse natural populations in the 1930s, and to Taiwan in 1981 (Wallentinus 1999; Zhang et al. 1984). In 1998, the production of wakame from natural populations in Japan amounted to 2839 tons valued at $8.3 million, while production from cultivation amounted to 70,670 tons valued at $132.5 million (H. Ohba, pers. comm.). Establishment of large populations of *Undaria* in California would almost certainly lead to harvesting by Asian immigrants, either for personal or commercial use.

In the northeastern Pacific, *Undaria* joins at least four other established Japanese seaweeds. The well-publicized brown alga *Sargassum muticum* (Yendo) Fensholt (Critchley et al. 1990) and green alga *Codium fragile* subsp. tomentosoides (van Goor) P.C. Silva (Trowbridge 1998), and the relatively unheralded red alga *Lomentaria hakodatensis* Yendo (Cabioc'h and Magne 1987), are widely distributed along the coast. The red alga *Gelidium vagum* Okamura has been found in Tomales Bay, California, where it was probably introduced from Japan by way of oyster farms in British Columbia and Washington (Renfrew et al. 1989; Hughey et al. 1996).

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