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Rapid Communication

The invasive brown alga *Undaria pinnatifida* (Harvey) Suringar, 1873 (Laminariales: Alariaceae), spreads northwards in Europe

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Abstract

The Asian kelp *Undaria pinnatifida* (Harvey) Suringar 1873 was found for the first time in Belfast Lough, Northern Ireland during 2012 and was probably established in 2013. This currently is the most northern locality in Europe. The recent expansion around Britain is likely to continue with further colonisation in Ireland and extension to Scotland. Conditions are suitable for colonisation of Celtic, North and perhaps Norwegian Sea coasts, where it is likely to become an important fouling organism on marinas, aquaculture equipment, and other structures. Its preponderance on marina and other pontoons suggests artificial structures are its preferred initial sites of colonisation.

Key words: Ireland, invasion, alien, wakame, marina, fouling, non-indigenous

Introduction

The Japanese kelp *Sargassum muticum* (Yendo) Fensholt is one of two brown algae that have spread to many continental coasts in the northern hemisphere. The Asian kelp *Undaria pinnatifida* (Harvey) Suringar, 1873, also known as *wakame* and *ito-wakame*, has followed a similar pattern of expansion and spread; but occurs in both hemispheres. These two kelps are native to coasts of the northwest Pacific Ocean from southeast Russia, China, Japan and Korea (Saito 1975; Kitayama et al. 1995). *U. pinnatifida* has an annual heteromorphic life cycle, alternating between the diploid sporophyte, which is easily recognised and may occur for up to nine months, and a microscopic haploid gametophyte stage. *U. pinnatifida* has expanded its range worldwide since the 1970s; it was recorded in New Zealand in 1987 (Hay and Luckens 1987; Stapleton 1988), Tasmania in 1988 (Sanderson 1990), and elsewhere in Australia in 1996 (Campbell and Burridge 1998; Sanderson 1990; Primo et al. 2010; Younger 2011). It appeared on the Pacific coast of the United States in 2000 (Silva et al. 2002; Thornbur et al. 2004) and more recently with flotsam (Tracy et al. 2012). It occurred in Mexico in 2003 (Aguilar-Rosas et al. 2004). This kelp was recorded in Patagonia, Argentina, in 1992 (Casas et al. 2004; Orensanz et al. 2002) and later found in northern Argentina in 2011 (Meretta et al. 2012).

Undaria pinnatifida was first discovered in Europe in 1971 in the Etang du Thau, France (Boudouresque et al. 1985). It is thought to have been introduced with Pacific oysters *Crassostrea gigas* (Thunberg, 1793) (Floc'h et al. 1991) (Figure 1), probably as the small and stress-tolerant gametophyte stage. In April 1992, this kelp appeared in the Venice Lagoon in the northern Adriatic Sea (Curiel et al. 1998), where it remains established (Curiel et al. 2002; D. Minchin pers. obs.), and at Taranto, southern Italy in 1998 (Cecere et al. 2000). *U. pinnatifida* was brought from the Etang du Thau and cultivated at different sites along the west coast of France in the 1980s and 1990s - in Brittany and on the Isle de Oleron (Perez et al.

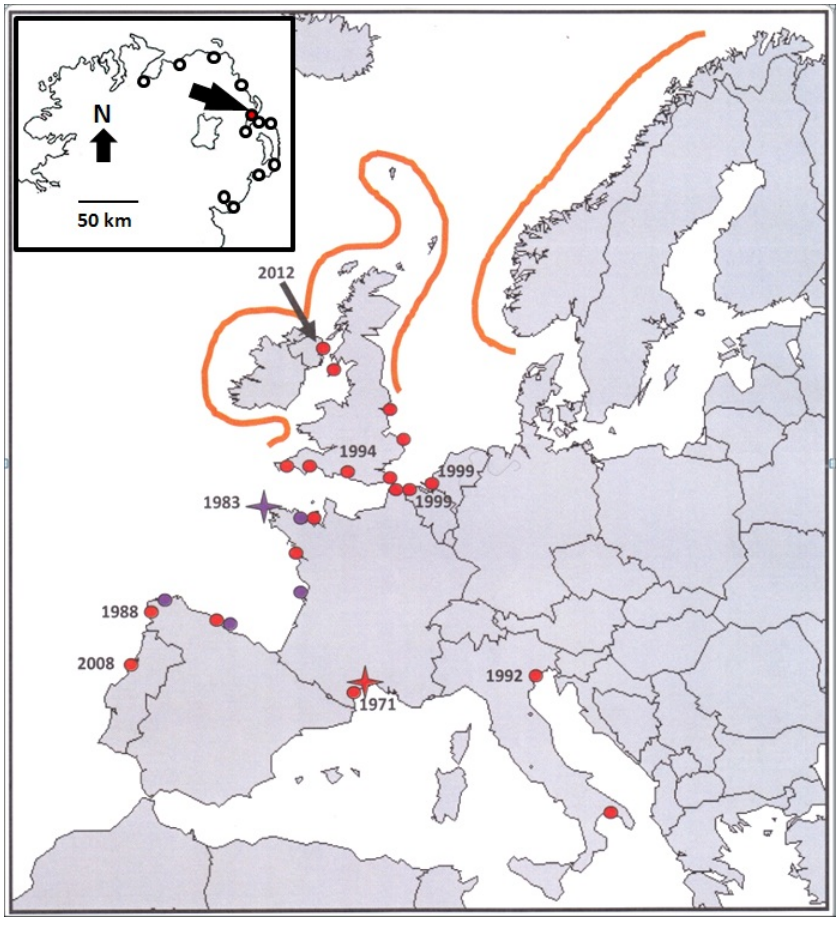

Figure 1. Distribution, showing dates of first records for each invaded country. Blue: cultivation of *U. pinnatifida*, Red: other populations. Red star: first Mediterranean record, Blue star first Atlantic record. The first Irish record arrowed. Lines indicate the probable future range of *U. pinnatifida*. For details see supplementary material Table 1S.

1984; Castric-Fey et al. 1996). It was in cultivation in Spain at Santander in 2000 (Peteiro 2008) and in Galicia (Peteiro and Freire 2011). The first record of the species occurring in the natural environment was close to the area of culture at Ousseant, Brittany, in 1986, just three years following its introduction for cultivation (Fletcher and Manfredi 1995). Since then, the kelp has been found in northern Spain (Santiago Caamaño et al. 1990; Cremades et al. 2006) and, in 2008, had spread into Portugal (MACOI 2008). Since its introduction for cultivation in the Atlantic, the alga gradually spread to Calais, northern France, in 1997; to Zeebruge, Belgium, in 1999 (Leliaert et al. 2000); and in the same year to Yerseke, The Netherlands (Stegenga 1999).

In Britain, *U. pinnatifida* was first discovered in the Hamble, Southampton Water, in June 1994 (Fletcher and Manfredi 1995). By 1998, it had spread to Cowes, some 12 km away, and to Torquay, which is >150 km from the Hamble, by 1996 (Fletcher and Farrell 1999) (Figure 1). Since then, this kelp has spread up the east coast, as isolated populations, as far north as the Humber Estuary and on the west coasts it spread to the Wyre Estuary and to the Isle of Man (NBN Gateway 2013). This account reports its finding from Belfast Lough, Northern Ireland, which is presently the most northern site for this species in Europe, and we discuss how *U. pinnatifida* may spread to sites even further north.

Methods

Undaria pinnatifida was one of several targeted non-indigenous species (NIS) in a survey of twelve marinas on the northern coastline of Ireland from the Foyle Estuary to Carlingford Lough (Figure 1). The target list was based on the expansion of NIS found elsewhere in Europe that might be expected to appear in Ireland.

Figure 2. Left, Carrickfergus marina, only used for berthing of leisure craft. Middle, Mature sporophyte plant found on 2 September 2012 from Carrickfergus Marina. Right, Fringing cover of *Undaria pinnatifida* at the Queen Anne Battery marina, Plymouth in October 2006. Photographs: DM and JN.

Thirty separate floating pontoon units were examined, representative of the entire expanse of each of the twelve marinas examined. Sampling consisted of using a scraper with a 15cm blade, mounted on a pole, to remove attached biota on the vertical face of each pontoon.

Water temperature was measured using an oceanographic reversing thermometer accurate to 0.1ºC at depths of 0.3 m to 0.5 m. Salinities were evaluated using a refractometer with an accuracy of ± 1. Water transparency was measured using a 30 cm diameter Secchi disc to the nearest 25 cm.

Sampling equipment was disinfected between sites using an iodine preparation (*Iosan ® CCT*: Ciba Geigy Agro Ltd, Waterford, Ireland).

The NBN Gateway (2013) database was examined to determine the cumulative frequencies of observed sporophytes by season, the year of first record, and the structures or natural surfaces, where *U. pinnatifida* was found.

Results

The field survey took place from 29 August to 8 September 2012. Only one marina, sampled on 2 September 2012 at Carrickfergus (Figure 2) in Belfast Lough (54º42'36.72"N, 05º48'47.45"W), provided three mature specimens of *U. pinnatifida*. All three specimens had sporophylls (Figure 2) and thus were capable of reproducing. Indeed, on 29 August 2013, one of us (JDN) revisited this marina to find hundreds of small plants attached near the surface of all pontoons examined within the marina.

Water temperatures ranged from 12.5 to 16.0ºC at all marina sites; at Carrickfergus Marina it was 14.5ºC. Salinities ranged between 1 and 35 and Secchi disc readings ranged between 0.5 m in an estuary to 4.0 m on the coast. At Carrickfergus Marina the salinity was 35 and the water transparency exceeded 2.0 m, enabling good observation of the fouling organisms on the pontoons.

In Britain, sporophytes were found mainly during the spring and summer and occurred most frequently at marina sites (Figure 3). The number of new records on the coast of Britain has been increasing since the species was first recorded in 1994 by Fletcher and Manfredi (1995).

Discussion

The three *U. pinnatifida* sporophytes found in 2012 (having probably arrived in 2011), and the presence of hundreds of smaller plants in the following year, indicate the species is established in Belfast Lough at Carrickfergus Marina. It is likely that the pontoons will develop an extensive fringing cover within a few years. One year after its discovery at the Queen Anne Battery marina in Plymouth, south-west Britain, in 2005 it had become the major fouling plant on pontoons (Figure 2). It is likely this kelp will spread to other sites in Ireland and northwards to Scotland and may even reach Orkney, the Shetlands, and Norway. It might expand its range as far north as the entrance to the Barents Sea where summer temperatures may attain ~10ºC (Ingvaldsen and Loeng 2009), which is sufficient for reproduction (Table 1). Colonisation is likely to take place where there are hard natural surfaces, aquaculture activities, marinas, and offshore structures. *U. pinnatifida* would appear to be spreading in British waters, with many new records appearing since 2010 (Figure 3). In time, it could become one of

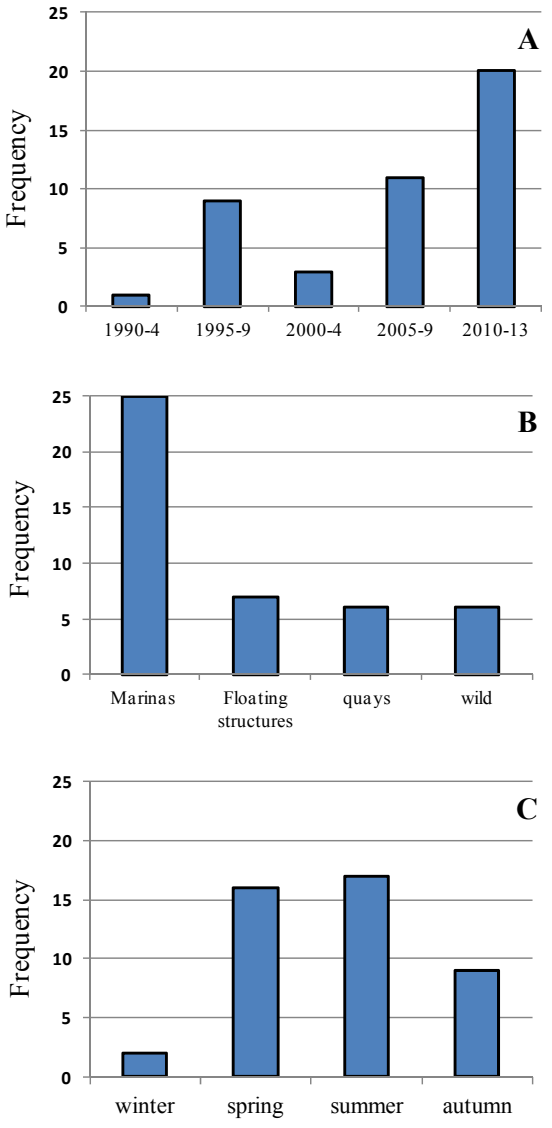

Figure 3. Frequency of records of *Undaria pinnatifida* in Britain according to year (A), sites of records (B), and season (C) (source: NBN Gateway 2013).

Table 1. Temperature tolerances for *Undaria pinnatifida* (modified from Sanderson 1990).

	Sporophyte	Gametophyte
Survival ranges	<0 – >25ºC	<-1 – 29ºC
Growth ranges	3.5 – 20ºC	10 – 24ºC
Reproductive ranges	7 – >23ºC	<10 – >24ºC

the dominant fouling species at many marinas and perhaps on mussel longlines, which has happened in Brittany (Castric-Fey et al. 1993). Attachment to the floatation units of fish cages might also take place, adding to drag where there are moderate to strong currents.

Undaria pinnatifida tolerates a range of exposure levels from sheltered marinas to moderately exposed coastal areas where aquaculture activities might be expected to take place (Sanderson 1997). In Brittany, plants were found close to the area of cultivation at depths to 5 m and occasionally down to 18 m (Floc'h et al. 1991) suggesting that fouling may not remain restricted to the near surface region. This kelp has the capability to invade and persist within native species assemblages and, when the community is disturbed, can become a dominant species (Forrest and Taylor 2002; Valentine and Johnson 2003). This very much depends on the time of year, and the level of succession of other algae, at the time sporophytes settle (Valentine and Johnson 2003). In Britain, sporophytes have been found throughout the year, with a preponderance of records during the spring and summer, which may relate to the optimal temperature conditions for sporophyte growth (Table 1). As a result, the timing of activities on an aquaculture site, or when launching leisure craft, may determine whether, and how many, sporophytes settle. This ability to foul vessels (Hay 1990) may depend upon the age, type, and condition of the antifouling on the vessels and the presence of untreated hull surfaces (Campbell and Hewitt 2013). Should antifouling paint be applied and maintained, it can be effective in reducing *U. pinnatifida* settlements (Burridge and Gorski 1997). The gametophyte stage readily settles on rope, and the movement of infected ropes and cage netting may also be a vector responsible for further range expansion.

The eventual geographical distribution of *U. pinnatifida* is likely to be limited to areas where salinities exceed 30, although it can endure occasional exposure to levels of 27 (Santiago Caamaña et al. 1990) or even 23 (Wallentinus 2007). Due to the requirement for fully saline conditions, it is unlikely that *U. pinnatifida* could become established in the low-salinity Baltic Sea. Temperatures about the Irish coast are suitable for growth, which is optimised at 5º–13ºC (Sanderson 1990; Hay and Villouta 1993) and which lies well within its overall tolerance range (Table 1). Recruitment of sporophytes takes place from 7º to 8ºC (Stuart and Brown 1996).

Sporophytes are generally intolerant of temperatures much over 20ºC and die-off occurs at 29ºC (Peters and Breeman 1992); however, these high temperatures are unlikely to occur in coastal waters of Ireland or further to the north.

The preponderance of *U. pinnatifida* at marina sites strongly implicates recreational craft in its spread (NBN Gateway 2013). Indeed, at one marina site in New Zealand, almost a quarter of the berthed leisure craft were fouled with sporophytes (Floerl et al. 2005). The high frequency of records in Britain from marina sites is consistent with observations in Europe and elsewhere (Table 2). The occurrence on quays may be as a result of inoculations from larger craft. While several vectors may be responsible for this kelp's distribution, the level of certainty varies with leisure craft dispersal being very likely (according to the proposed classification by Minchin 2007) (Table 2). The suggestion that *U. pinnatifida* may be spread by ballast water by Sanderson (1990) is unlikely to happen. This is because spores, should they be taken up with ballasted water, are expected to perish. For completion of their life-cycle spores must develop into gametophytes, followed by settlement onto a hard substrate, and then fertilisation. Suitable conditions for this development are unlikely in the dark inside of ballast tanks (Mineur pers. comm.).

U. pinnatifida spores are thought to be naturally capable of spreading over tens to hundreds of metres (Forrest et al. 2000). Fertile sporophytes, which carry great numbers of spores, can be dispersed as drifting wrack by strong tidal currents and storm events (Table 2). Should sporophytes attach to shells and stones, currents can drag plants as the lamina grows larger. Drift sporophyte plants were noticed in Plymouth in the Plym Estuary during October 2006 (DM pers. ob.). Thus annual dispersal by natural means could be in the order of several kilometres (Casas and Piriz 1996; Floc'h et al. 1996; Sanderson, 1997; Curiel et al. 1998). Its appearance on natural substrates would appear to take some years following establishment at a nearby marina or culture site. For example, in Torquay, south Britain, this took up to seven years (Farrell and Fletcher 2006). Nevertheless, the number of records during the current decade indicates a continued expansion (Figure 3) with the increase in such records possibly aided by public involvement. However, Mineur et al. (2008) in a survey showed that most members of the public, while aware of invasive species, were unaware of *U. pinnatifida*.

The arrival of *U. pinnatifida* on the Atlantic coast of Europe was as a result of plants being moved from the Etang du Thau in 1983 for cultivation in Brittany (Floc'h et al. 1991). Cultivation was also practiced in Spain (Peteiro 2008), and there were intentions to cultivate it on the west coast of Ireland in 1991 but the proposal was not permitted to proceed. In Asia, the maximum production was 2.4 million tonnes in 2005 (FAO 2013). However, the Atlantic production is low and some farms have discontinued attempts at production. The spread of this kelp in Europe is likely to continue with ongoing transplanting of half-grown molluscs used for culture or for stocking. Since the small gametophyte stage tolerates aerial exposure under damp conditions for several days (Kim and Nam 1997), it may become widespread.

A process for evaluating the impact on the environment, social values and the costs in relation to protected areas, using *U. pinnatifida* as an example, could be developed and applied to impacts on aquaculture activities and production, marina and port management, as well as special protected areas in a manner similar to that undertaken by Campbell and Hewitt (2013) for New Zealand reserves. We think the main risks for dispersal are fouling on small crafts and the movements of aquaculture or ranched stock. In the Marine Strategy Framework Directive (European Commission 2008) survey work, *U. pinnatifida* should be treated as a target species, especially when using marinas in rapid assessment surveys as was undertaken by Ashton et al. (2006). However, measures to eradicate *U. pinnatifida* are unlikely to be successful (Hewitt et al. 2005; Wallentinus 2007) due to the numerous modes of dispersal and different life-history stages: the small gametophyte stage is easily overlooked. Where elimination has been successful, the costs have been high and duration of the treatment exceeded two years (Wotton et al. 2004).

Conclusion

It is unlikely that Belfast Lough will house the most northerly population of *U. pinnatifida* in Europe for long, with its expected ultimate expansion to Celtic, North, and perhaps Norwegian Sea coasts. While its spread in the past has been moderate, the increase in records this decade could mean a rapid increase in its range over the coming years. Environmental conditions are suitable for its growth and reproduction. *U. pinnatifida* is likely to first appear on anthropogenic structures,

in particular marinas, spread as fouling on the hulls of small craft, aquaculture equipment and mollusc stock movements. When undertaking surveys that include *U. pinnatifida*, marinas should be one of the first areas examined.

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Supplementary material

The following supplementary material is available for this article:

Table 1S. Records of *Undaria pinnatifida* in Europe.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2014/Supplements/BIR_2014_Minchin_Nunn_Supplement.xls