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Assessing the extent of establishment of *Undaria pinnatifida* in Plymouth Sound Special Area of Conservation, UK

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The north-west Pacific kelp, Undaria pinnatifida, *was first discovered in Europe on the Mediterranean coast of France (1971) and introduced to Brittany for aquaculture (1983). In the north-east Atlantic, it occurs in Spain, France, the British Isles, Belgium and Holland. The first UK record was in the Hamble estuary (1994) and it was found off Plymouth in 2003. The UK distribution is presently restricted to the south of England and the northern Irish Sea. We assessed the distribution of* U. pinnatifida *and native kelps and their allies in Plymouth Sound (at 0 to +1 m relative to Chart Datum).* Undaria pinnatifida *was widespread along rocky shores, on other hard substrata and grew in the same areas as* Saccharina latissima *and* Saccorhiza polyschides. Undaria pinnatifida *was significantly more abundant on vertical substrata than on upward-facing hard substrata. It was almost as common as all of the other kelp species combined on vertical substrata but was outnumbered by native species on upward-facing substrata.* Undaria pinnatifida *has become the visually dominant macroalga in marinas and has spread to surrounding natural habitats in Plymouth Sound. The extent to which it will outcompete native kelps requires monitoring, especially in conservation areas.*

Keywords: *Undaria pinnatifida*, non-native, invasions, establishment, Plymouth Sound, orientation, spread

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INTRODUCTION

Non-native marine and terrestrial species impose high economic costs worldwide (Pimentel *et al.*, 2001). For the UK alone, the costs are estimated to be £1.7 billion per year (Williams *et al.*, 2010). Non-native and non-indigenous species are those that have been introduced by humans into an area historically outside their range and they then successfully reproduce and maintain a population within the new area (Eno *et al.*, 1997; Reise *et al.*, 2006). The temperate northern Pacific, the eastern Indo-Pacific and the temperate North Atlantic are often hotspots for marine invasive species (Molnar *et al.*, 2008). Non-native seaweeds pose a threat as they are able to change ecosystem structure and functioning (Schaffelke *et al.*, 2006). However, worldwide only 6% of non-native seaweeds (17 species) have had their ecological effects on ecosystems evaluated (Williams & Smith, 2007). In terrestrial and freshwater ecosystems, non-native species may have devastating consequences for native species. In Britain, examples include the loss of flora from areas due to domination by *Rhododendron ponticum* L. and *Fallopia japonica* Houtt. (Ronse Decr.) (Japanese knotweed) or the introduction of diseases. Non-native species are also known to outcompete native species for habitat, such as by *Pacifastacus leniusculus* (Dana, 1852) (signal crayfish) or to cause commercial impacts such as clogging cooling water intakes (*Dreissena polymorpha* (Pallas, 1771) the zebra mussel). Although many non-native species do not have major disruptive effects on native communities, and may even increase food availability or habitats for native species, some threaten to overwhelm native species and can also be a threat to commercial activities (Williams *et al.*, 2010). For instance, slipper limpets (*Crepidula fornicata* (L., 1758)) are a serious pest of oyster and mussel beds whilst it is estimated that the carpet sea squirt *Didemnum vexillum* Kott, 2002 could cost mussel farming between £1.3 and £6.8 million in the next ten years. A species of seaweed present in Britain since 1973, the Asian *Sargassum muticum* (Yendo) Fensholt, is visually dominant in many areas and has the potential to foul propellers and reduce access to areas (information on non-native species is provided on the Great Britain Non-Native Species Secretariat web pages where Risk Assessments include bibliographies: www.nonnativespecies.org).

The kelp *Undaria pinnatifida* (Harvey) Suringar is one of the most invasive seaweeds worldwide (Trowbridge, 2006; ICES, 2007; Williams & Smith, 2007); it is an annual kelp with a macroscopic sporophyte and a microscopic gametophyte (Floc'h *et al.*, 1991; Morita *et al.*, 2003). In its native range, which is in the north-west Pacific, sporophytes are present between autumn and mid-spring (Morita *et al.*, 2003). However, in areas it has successfully invaded, sporophytes are present throughout the year (e.g. Hay, 1990; Fletcher & Manfredi, 1995). In Plymouth Sound Special

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Area of Conservation (SAC) we have observed young sporophytes nearly all year. The outer boundary of the SAC is 3 km south of the Breakwater and it extends along the Tamar but does not include the Plym estuary. *Undaria pinnatifida* is known as 'Japanese kelp' and also as 'wakame' and has long been eaten by humans (Morita *et al.*, 2003; Peteiro & Freire, 2011). Currently it is also part of the European diet due to its high quality in taste and nutrition (Peteiro & Freire, 2011).

Besides a hardy aquarium strain of the tropical seaweed *Caulerpa taxifolia* (M. Vahl) C. Agardh, *Undaria pinnatfida* is the only other marine macroalgae identified as one of the 100 most invasive species of the world in the list maintained by the Invasive Species Specialist Group (Lowe *et al.*, 2000). In Europe *U. pinnatifida* has been ranked as the third most invasive seaweed, from a range of 113 species, and has been transported by boats and through aquaculture (Nyberg & Wallentinus, 2005; ICES, 2007). It was first introduced to southern France, possibly accidently together with oysters, and in 1983 deliberate cultivation of this species began on the North Atlantic coast of Brittany (Fletcher & Farrell, 1999). It is now widely distributed in the world's oceans including the northern Mediterranean, north-east Atlantic, south-west Pacific, Tasman Sea, south-west Atlantic, east Pacific and parts of the north-west Pacific where it has not occurred formerly (Trowbridge, 2006; ICES, 2007). In European waters it has reached France, Italy, Spain, England, Holland and Belgium (ICES, 2007). Its spread however is expected to have increased since then and recent observations in September 2012 (Julia Nunn and Chris Frid, personal communications) have recorded the species from north-east Ireland and Liverpool.

First records for the British Isles were from the Hamble estuary, southern England, in June 1994 (Fletcher & Manfredi, 1995). *Undaria pinnatifida* has since spread to several locations along the south coast (Arenas *et al.*, 2006; ICES, 2007), including Plymouth Sound and associated estuaries. It was first recorded by KeithHiscock in May 2003 in the Plymouth Yacht Haven marina (National Biodiversity Network, 2012), which is in the Cattewater at the mouth of the Plym estuary. Since then, *U. pinnatifida* has been observed in several locations around Plymouth Sound but estimates of its abundance at different locations vary considerably from two individuals to abundant (MarLIN, 2012). It occurs between +1 m to −7 m relative to Chart Datum (K.H. and J.H.-S., personal observations).

In this study, quantitative data are provided on the occurrence of *Undaria pinnatfida* in Plymouth Sound. These data form a baseline for future studies enabling the monitoring of changes in abundance and distribution of *U. pinnatifida* and other observed species over time. Furthermore, its settlement on vertical and upward-facing surfaces is assessed in comparison to native kelps and other large phaeophytes.

MATERIALS AND METHODS

Data collection

Between August and September 2011 snorkellers surveyed 17 sites within Plymouth Sound (Figure 1; Table 1) which were chosen due to their distribution around the sound and accessibility. The survey took place between 0 to +1 m relative to Chart Datum (or at sea level in the case of floating pontoons). At most sites, 30 quadrats (50 × 50 cm) were placed haphazardly on vertical surfaces and 30 quadrats on upward-facing surfaces. The surveyor either placed the quadrat blindly on vertical or steeply sloping surfaces or dropped it from a

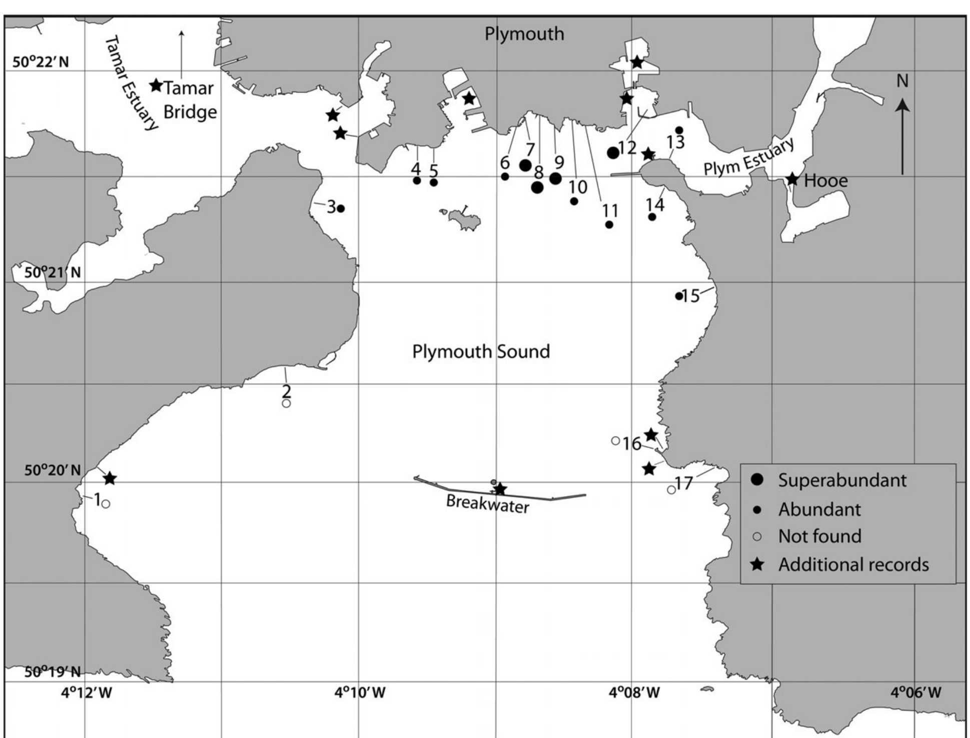

Fig. 1. Distribution of *Undaria pinnatifida* (Harvey) Suringar off Plymouth (0.25 m^2 quadrats were used, N = 60, except for sites 4, 5, 7 and 13 where N = 30). Superabundant = 10–99 individuals per m^2; abundant = 1–9 individuals per m^2.

Fig. 1 - B/W online

Table 1. Site description for each site. No data are available for *. Substratum: B, bedrock; VLB; very large boulders (>1024 mm); LB, large boulders (512–1024 mm); SB; small boulders (256–512 mm; C, cobbles (64–256 mm); P, pebbles (16–64 mm); GS, gravel stone (4–16 mm); SC, sand coarse (1–4 mm); SM, sand medium (0.25–1 mm); SF, sand fine (0.063–0.25 mm); M, mud (<0.063 mm). The substratum sizes are those developed by the Marine Nature Conservation Review of Great Britain (Connor & Hiscock, 1996). Uses and impacts: A, angling; LC, land claim; LD; litter and debris; ESS, educational/scientific study; PB, popular beach; M, marina; WS; water sports; DS, dive site; MBL, mooring/beaching/launching. Temp., temperature.

Site	Site name	Date of survey	Temp. water (°C)	Temp. air (°C)	Salinity in ppt	pH	Substratum	Wave exposure	Tidal streams	Geology	Uses and impacts
1	Kingsand/Caw-sand Bay	27/08/2011	16.7	17.2	34.5	8.16	50% B 10% C 10% P 30% SC	Moderately exposed	Moderately strong	Sand/limestone	ESS, PB, WS, DS, MBL
2	Fort Picklecombe	01/09/2011	19.1	23.0	*	*	80% B 10% C 5% P 5% SC	Exposed	Weak	Sand/limestone	ESS
3	Barnpool	27/08/2011	17.3	17.4	33.3	8.3	10% B 25% VLB 10% C 10% P 10% GS 10% SC 10% SM 10% SF 5% M	Moderately exposed	Moderately strong	Sand/limestone	ESS, DS
4	Firestone Bay	11/08/2011	17.5	21.2	33.6	8.01	30% B 50% LB 10% C 10% P	Sheltered	Moderately strong	Sand/limestone	A, LC (artificial pool), LD (from individuals), ESS, DS
5	Firestone Bay	11/08/2011	17.2	21.3	33.9	7.97	30% B 50% LB 20% M	Sheltered	Moderately strong	Sand/limestone	A, LD (individuals), ESS, DS
6	West Hoe	05/08/2011	17.8	21.9	32.4	8.27	90% B 10% VLB	Sheltered	Weak	Sand/limestone	A, LC (artificial wall), LD (from individuals), ESS, WS (jet ski), DS
7	West Hoe	05/08/2011	17.0	21.9	29.6	7.62	80% B 10% LG 10% GS	Sheltered	Weak	sand/Limestone	A, LC (artificial wall), LD (from individuals), ESS, WS (jet ski), DS
8	West of Lido	13/08/2011	16.1	*	34.2	8.19	50% B 10% LG 40% C	Sheltered	Weak	Sand/limestone	LC (walls, steps), LD (individuals), ESS, WS (jet skis), MBL (small tourist boats)

Continued

Table 1. Continued

Site	Site name	Date of survey	Temp. water (°C)	Temp. air (°C)	Salinity in ppt	pH	Substratum	Wave exposure	Tidal streams	Geology	Uses and impacts
9	West of Lido	13/08/2011	16.1	*	34.1	8.17	50% B 10% VLB 10% LB 30% C	Sheltered	Weak	Sand/limestone	LC (walls, steps), LD (individuals), ESS, WS (jet skis), MBL (small tourist boats)
10	East of Lido	20/08/2011	16.1	*	34.0	8.19	50% B 20% LB 10% C 10% P 5% GS 5% SC	Sheltered	Weak	Sand/limestone	A, LD (individuals), ESS, PB (swimming)
11	East of Lido	20/08/2011	16.1	*	34.1	8.14	50% B 20% VLB 20% LB 10% C	Sheltered	Weak	Sand/limestone	A, LD (individuals), ESS
12	Queen Anne's Battery	25/08/2011	*	*	*	*	NA	Sheltered	Weak	Concrete/ polystyrene decking with steel frames	LC (marina), LD (individuals, marina), M, MBL
13	Mountbatten Pontoon	18/08/2011	16.9	*	32.0	8.16	NA	Moderately exposed	Moderately strong	Mild steel coated in two pack paint system	LC (artificial pontoon, floating), LD (individuals), ESS, M, WS (surfing, canoeing, etc), MBL (dive boats)
14	Mountbatten Bay	18/08/2011	16.7	*	33.6	8.15	70% B 20% LB 10% C	Moderately exposed	Weak	Sand/limestone	LD (individuals, a lot carried there through currents), ESS
15	Jennycliff	26/08/2011	16.9	18.3	33.7	8.11	50% B 20% C 20% P 10% SC	Moderately exposed	Moderately strong	Sand/limestone	LD (through current), ESS, DS
16	Bovisand Harbour	23/08/2011	16.2	16.7	33.6	8.05	70% B 5% C 5% P 10% GS 10% SC	Moderately exposed	Moderately strong–weak	Sand/limestone	A, LC (harbour), ESS, DS, MBL (dive boats)
17	Bovisand	26/08/2011	16.3	16.7	32.3	7.94	70% B 10% C 20% SC	Moderately exposed	Moderately strong	Sand/limestone	ESS, PB, WS (surfing), DS

height, respectively. Sites 4 and 5 lacked vertical surfaces, at site 7 only 15 quadrats for each orientation were surveyed, and at sites 12 and 13 only vertical surfaces of marina pontoons were surveyed (the other sites were rocky). In each quadrat Laminariales and Tilopteridales were counted, the species observed were: *Laminaria digitata* (Hudson) J.V. Lamouroux; *Laminaria hyperborea* (Gunnerus) Foslie; *Laminaria ochroleuca* Bachelot de la Pylaie; *Saccharina latissima* (Linnaeus) C.E. Lane, C. Mayes, Druehl & G.W. Saunders; *Saccorhiza polyschides* (Lightfoot) Batters; and *Undaria pinnatifida*. The area surveyed at each site depended on the local topography along the coast (how large an area was of suitable substratum) and steepness of the slope seawards (how wide was the zone which was within the required depth of 0 to +1 m relative to Chart Datum). It was generally over about a 20 m length of coastline. At each site, salinity, pH and temperature were measured using a pH-multimeter and general characteristics of the site were noted such as substratum type and percentage cover, wave exposure, tidal streams and the uses and impacts on the site.

Data analysis

The data were converted from individuals per 0.25 m² to individuals per 1 m². The mean (± standard error (SE)) abundance of individuals per m² was calculated and displayed in bar graphs including error bars. All data were tested for equal distribution with the Kolmogorov–Smirnov test from Minitab 16. As the data were not equally distributed, the non-parametric Mann–Whitney test (*U*) was used for differences between groups. In order to account for multiple testing, the Bonferroni method was used to adjust *P* values.

The map used to display the distribution of *Undaria pinnatifida* in Plymouth Sound SAC was retrieved from Digimap Collections (2011). Our abundance data were converted into the SACFOR abundance scale (Connor & Hiscock, 1996) and mean abundance of each species was calculated for sites with and without *U. pinnatifida* and for upward-facing and vertical surfaces (excluding sites 4, 5, 12 and 13, which only had vertical surfaces).

RESULTS

Distribution of *Undaria pinnatifida*

The distribution of *Undaria pinnatifida* sporophytes around Plymouth Sound in summer 2011 is shown in Figure 1; with site descriptions given in Table 1. Plants were found on shallow hard substrata consisting mainly of sand and sandstone (Table 1) throughout Plymouth Sound north of the Breakwater, to Saltash in the Tamar estuary and to Hooe in the Plym estuary. The highest abundance was found in a marina (site 12, 24 ind. m^{-2} ± SE 2.0; Table 1) on pontoon floats made out of concrete. Wherever *U. pinnatifida* was found it was superabundant (10–99 m^{-2}) or abundant (1–9 m^{-2}) on the SACFOR scale.

At sites where *U. pinnatifida* was present all other Laminariales and Tilopteridales were significantly lower in abundance (Figure 2). *Saccharina latissima* and *Saccorhiza polyschides* were significantly more abundant at sites with *U. pinnatifida* whereas *Laminaria digitata*, *L. hyperborea* and *L. ochroleuca* were significantly more abundant at sites without *U. pinnatifida*.

On upward-facing surfaces there was no significant difference in abundance between *Undaria pinnatifida* and the other Laminariales and Tilopteridales present (Figure 3). *Undaria pinnatifida* was twice as abundant on vertical surfaces as on upward-facing surfaces. *Saccharina latissima, Saccorhiza polyschides, Laminaria digitata* and *L. hyperborea* were significantly less abundant on vertical than on upward-facing surfaces. On vertical surfaces, *U. pinnatifida* was significantly more abundant than the other large phaeophytes present.

Fig. 2 - B/W online

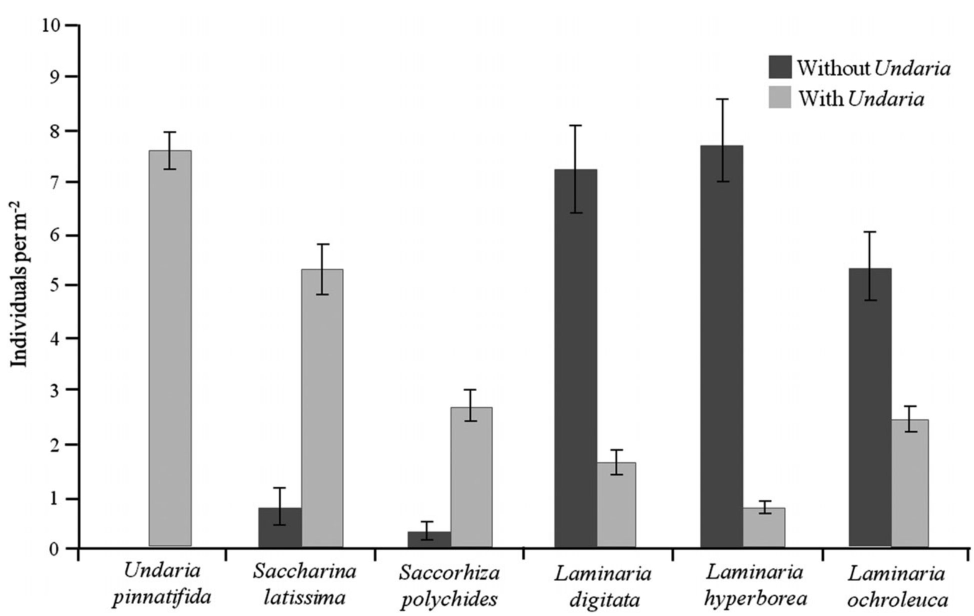

Fig. 2. Mean (± standard error) abundance of Laminariales and Tilopteridales at sites with *Undaria pinnatifida* (Harvey) Suringar (N = 510) and without *U. pinnatifida* (N = 240), excluding sites 4, 5, 12 and 13. *Undaria pinnatifida* present: all other Laminariales and Tilopteridales significantly lower in abundance, *Saccharina latissima* and *Saccorhiza polyschides* significantly more abundant than on sites without *U. pinnatifida*. Without *U. pinnatifida*: *Laminaria digitata*, *Laminaria hyperborea* and *Laminaria ochroleuca* significantly more abundant than at sites with *U. pinnatifida*.

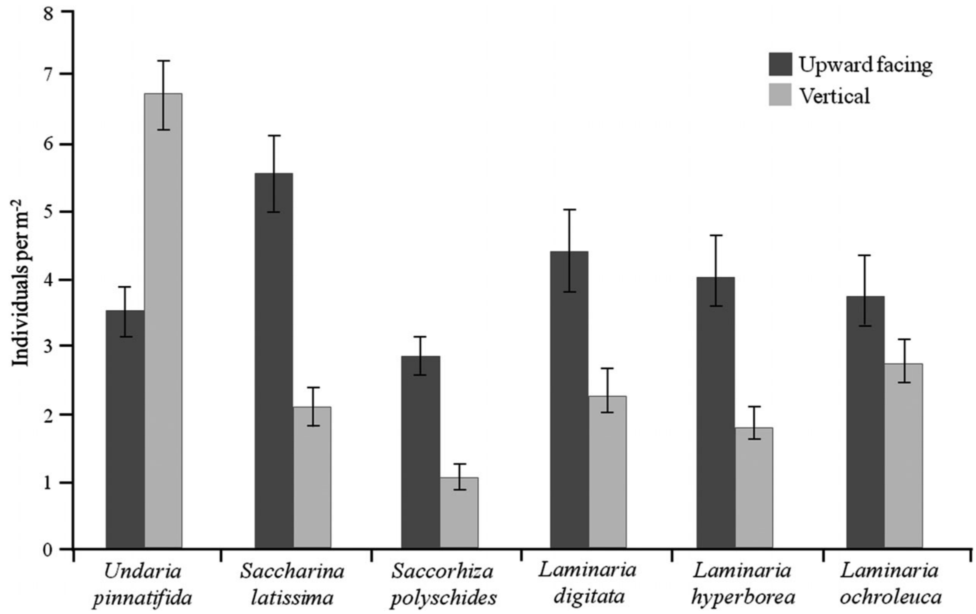

Fig. 3 - B/W online

Fig. 3. Mean (± standard error) abundance of Laminariales and Tilopteridales on upward-facing and on vertical surfaces (N = 375) for all sites excluding 4, 5, 12 and 13. Upward-facing: no significant difference between *Undaria pinnatifida* and other Laminariales and Tilopteridales; *U. pinnatifida* was twice as abundant on vertical surfaces as on upward-facing surfaces; *Saccharina latissima*, *Saccorhiza polyschides*, *Laminaria digitata* and *Laminaria hyperborea* significantly less abundant on vertical than on upward-facing surfaces; vertical: *U. pinnatifida* significantly more abundant than the other Laminariales and Tilopteridales.

DISCUSSION

Distribution of *Undaria pinnatifida*

By summer 2011, *Undaria pinnatifida* had become well established within Plymouth Sound SAC. The first occurrence and the highest abundance were observed in marinas (Plymouth Yacht Haven and Queen Anne's Battery, respectively), which are both visited by boats from all over the world. This indicates that the vector for introduction to Plymouth has been boat traffic, the same suspected vector as at other sites on the south coast of England, like the Hamble estuary where it was first recorded in Britain (Fletcher & Manfredi, 1995). In our surveys, sites with *U. pinnatifida* present were more sheltered from wave exposure and most had weak surface tidal streams (Table 1).

Undaria pinnatifida grew in the same habitat as *Saccharina latissima* and *Saccorhiza polyschides* and was the dominant macroalga in that association. Floc'h *et al.* (1991) suggested that *Undaria* is not very competitive, especially compared to the annual *S. polyschides*. However, Casas *et al.* (2004) found that *U. pinnatifida* can outcompete native species at certain times of year. Hay (1990) identified three characteristics of *U. pinnatifida* that could increase its competitive interactions with native algae. First, new or recently disturbed areas are quickly colonized. Second, compared to local annuals its propagules settle throughout the year and mature to reproducing sporophytes. Third, it is able to colonize artificial substrata successfully. We found that the invasive kelp was especially dominant on vertical surfaces and concur with the findings of Farrell & Fletcher (2006) that *U. pinnatifida* tolerates turbidity and siltation better than native kelps.

Ecological impact

Undaria pinnatifida has become established throughout Plymouth Sound and extends into the associated estuaries. It has become visually dominant during the summer at some locations, especially on shallow vertical surfaces where other kelp species do not flourish. We do not yet know whether native species will be outcompeted by *U. pinnatifida* although observations made in summer 2013 suggest that it is continuing to spread into habitats occupied by native kelps off Plymouth (J.H.S. and K.H. personal observations). The highly invasive fucalean alga *Sargassum muticum* competes with native macroalgae (Stæhr *et al.*, 2000; Britton-Simmons, 2004) but has not adversely affected biodiversity levels (Hopkins, 2002; Ribera Sagun, 2002; Streftaris *et al.*, 2005). As *S. muticum* is able to settle in sites with low prevailing heterogeneity it can increase epifaunal biodiversity and abundance by adding structural features to the habitat (Buschbaum *et al.*, 2006). However, White & Shurin (2011) identified that, at high cover, *S. muticum* excludes native species and reduces richness through light competition by shading smaller, understory macroalgae. *Undaria pinnatifida* is likely to have a much higher shading effect than *S. muticum* as, when submerged, *S. muticum* floats vertically and has a very small 'footprint' whereas *U. pinnatifida* remains draped over the substratum when submerged or in subtidal habitats and is likely to have a much greater shading or smothering effect than *S. muticum*. Given the spread of *U. pinnatifida* in nature conservation areas ecological interactions with other flora and fauna need to be assessed. Wherever we found *U. pinnatifida* around Plymouth during spring to late summer, it was abundant and often the visually dominant species; we are concerned that *U. pinnatifida* may outcompete native macroalgae and cause community shifts. Furthermore, since *U. pinnatifida* currently thrives in warmer waters in its native Japan rather than those of southern Britain (Pinet, 2009), it is likely to spread north as sea surface temperatures warm.

Abiotic and biotic factors are likely to influence the further spread of *Undaria pinnatifida* and its ecological impact. In

New Zealand, Thompson & Schiel (2012) found that *U. pinnatifida* settlement and growth was facilitated by coralline turf algae but inhibited by a native fucoid (*Carpophyllum maschalocarpum*) and Thornber *et al.* (2004) found that native crabs consumed *U. pinnatifida*.

The collection of baseline data and rigorous monitoring for non-native species is especially important for SACs such as Plymouth Sound where *Undaria pinnatifida* is spreading rapidly. An aim of SACs is to conserve natural habitats although it is difficult to prevent the replacement of native species by non-natives. Once *U. pinnatifida* has settled and grown to mature sporophytes it resists most attempts at long-term removal (Fletcher & Farrell, 1999). One of the few successful eradication attempts was undertaken in the Chatham Islands (New Zealand) where a sunken ship was completely cleared of the non-native kelp through heat treatment at 70°C that prevented further spread onto adjacent natural habitats (Wotton *et al.*, 2004). Manual removal was successful in controlling (but not eradicating) *U. pinnatifida* in a Tasmanian marine reserve (Hewitt *et al.,* 2005) with the authors concluding that, to be effective, 'a long-term commitment to a removal activity needs to be coupled with vector management and education initiatives to reduce the chances of re-inoculation and spread, with monitoring (and response) on a larger spatial scale for early detection of other incursion sites, and with treatment to remove persistent microscopic stages'. A record of eradication or control attempts worldwide and their success is maintained on the Global Invasive Species Database (www.issg.org). We conclude that it is essential that the spread of *U. pinnatifida* is monitored, taking substratum orientation into account, especially when reporting on 'favourable conservation status' of SACs. The impact of this rapidly spreading invasive kelp on local ecosystems also needs to be assessed to establish whether eradication or control should be attempted.

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