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The establishment of the invasive non-native macroalga *Sargassum muticum* in the north of Scotland

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Abstract

The spread of the brown seaweed *Sargassum muticum* is one of the best documented invasions of a non-native marine species. Observation of a potentially established population of *S. muticum* in the Orkney Islands archipelago, located off the northern coast of Scotland, was reported by recreational snorkellers in 2019 and 2020. The present study summarises a focussed investigation to confirm its presence and current local distribution, using data from 46 survey sites monitored as a part of the Orkney Islands Council Harbour Authority monitoring programme. Findings in this study represent the most northerly record of an established population of *S. muticum* in the United Kingdom, extending the latitudinal range in this country by 1.44° (159 km) northwards, and indicate only localised presence of this species. Analysis of a partial cytochrome oxidase I gene sequence confirmed the visual species identification. Possible vectors of introduction, gaps in the geographic range, local ecological and economic impacts, and the potential ameliorating factor of deep rockpools on wave exposed shores for *S. muticum* are discussed.

Introduction

Sargassum muticum (Yendo) Fensholt, commonly known as Wireweed, is a monoecious brown macroalga belonging to the order *Fucales* (Norton, 1976). One of its distinguishing characteristics is the presence of numerous small air bladders that provide buoyancy to the fronds (Rueness, 1989). In its native Japanese waters, *S. muticum* fronds typically grow to 1–1.5 m (Rueness, 1989), from littoral to shallow sublittoral depths (Norton, 1977; Knoepffler-Peguy *et al.*, 1985; Stæhr *et al.*, 2000). Outside of its native range, *S. muticum* has low substrate specificity, being commonly found on hard natural and artificial surfaces, as well as attached to shell fragments or coarse sediments, and embedded in mud (Critchley *et al.*, 1983; Knoepffler-Peguy *et al.*, 1985; Tweedley, 2008). This seaweed is tolerant to wide ranges of temperature (−1 to 25°C) and salinity (Norton, 1977; Steen, 2004), although some studies indicate reproductive failure following prolonged exposure to salinities below 15‰ (Kjeldsen and Pinney 1972; Steen 2004). *Sargassum muticum* can be found on sheltered to moderately exposed shores (Deysher and Norton, 1982; Sanchez *et al.*, 2005), but requires protection from extreme wave action (Critchley *et al.*, 1983). At small scales, abundance of *S. muticum* correlates with differences in depth and substrate (Stæhr *et al.*, 2000).

Pathways/vectors of spread and establishment

Two main means of natural dispersal are utilised by *S. muticum*: release of planktonic propagules into the water column, and breaking free of floating vegetative fronds, assisted by the air-bladders (Rueness, 1989). The former means may result in dispersal over relatively limited range, typically on a scale of metres, with germlings detected up to 1.3 km from reproductively active adults (Deysher and Norton, 1982); the latter means may result in dispersal over extensive distances on a scale of tens or even hundreds of kilometres (Deysher and Norton, 1982). In both strategies, the direction and speed of wind and currents drive the dispersal range (Deysher and Norton, 1982; Stæhr *et al.*, 2000).

In addition to rafting or floating of entire plants or detached fragments (Kraan, 2008), long distance dispersal of *S. muticum* can be facilitated through anthropogenic vectors (Davison, 2009). Evidence suggests that the transportation of shellfish for aquaculture, e.g. oysters, may be one of the primary means of introduction of *S. muticum* (Deysher and Norton, 1982; Critchley, 1983). Other potential vectors may include entanglement of fragments in anchor chains and steering gear (Harries *et al.*, 2007), attachment to ship hulls or transportation in ballast water (Kraan, 2008). Hulls and ballast tanks, however, may not be suitable for the transport of germlings of *S. muticum* (Deysher and Norton, 1982; Engelen *et al.*, 2015).

Impacts on local biodiversity and potential economic impacts

In its native waters, *S. muticum* is an unremarkable member of the littoral community (Rueness, 1989). However, in introduced regions, *Sargassum* tends to form dense beds that may replace native vegetation (Druel, 1973; Farnham *et al*., 1973; Rueness, 1989), resulting in reduced local biodiversity. The growth rate of this alga has been shown to far exceed that of other fucoids in comparative studies (Norton, 1977; Nicholson *et al*., 1981) and individuals have been recorded up to 16 m in length (Vaz-Pinto *et al*., 2014). The expansive canopy-forming capacity of rapidly growing *S. muticum* may help outcompete other key macroalgae for space and light, producing systemic impacts on the local community and habitats (Ambrose and Nelson, 1982; Cosson, 1999; Stæhr *et al*., 2000; Sanchez *et al*., 2005; Engelen *et al*., 2015). Dense stands may also reduce water motion (Deysher and Norton, 1982).

The rapid growth and success of *S. muticum* in introduced waters may be an example of the enemy release hypothesis (Elton, 1958), wherein *S. muticum* as an introduced non-native species (NNS) is released from certain pressures that impact native seaweeds. Indeed, studies of macroalgal grazers in Portugal indicated preference for feeding on native seaweed compared with *S. muticum* (Engelen *et al*., 2011). Furthermore, recent studies of the microbiome associated with *S. muticum* reveal this species may benefit by being a generalist host (Aires *et al*., 2022). Ready replacement of its microbiome in new geographic regions may be another means by which *S. muticum* is able to spread so effectively.

The establishment of *S. muticum* in a new habitat appears to reduce the abundance of the existing dominant seaweed, especially 'leathery' macroalgae (Viejo *et al*., 1995; Stæhr *et al*., 2000; Engelen *et al*., 2015). This replacement of dominance may extend to other photosynthesising species, such as seagrass (den Hartog *et al*., 1997; Tweedley, 2008). Impacts to local biodiversity may result in fewer species and reduced ecosystem complexity (Stæhr *et al*., 2000; Engelen *et al*., 2015). Conversely, studies in Spanish waters report increased biodiversity of opportunistic epiphytic species and primary productivity following establishment of *S. muticum* (Sanchez *et al*., 2005); the potential changes to ecosystem services, as a consequence of these changes, could not be ascertained.

From an economic perspective, biofouling of netting and other gear is a concern to fishers (Critchley *et al*., 1986). Drift material from *S. muticum* can foul propellers and clog water intakes on ships and aquaculture and other industrial facilities (Critchley *et al*., 1986). Floating masses of seaweed may cause a loss in amenities and associated recreational activity, i.e. swimming, surfing, sailing, etc. (Eno *et al*., 1997).

The spread of *S. muticum* in Europe and the UK

Sargassum muticum is native to Japanese waters (Norton, 1977), from the Sea of Okhotsk to Shanghai, China (National Biodiversity Network, 2023a). After appearing on the west coast of North America in the 1940s (Norton, 1977; Ribera and Boudouresque, 1995), the first record of attached *S. muticum* in European waters was reported from Bembridge, Isle of Wight in 1973 (Farnham *et al*., 1973). However, drift material had been observed the previous year in the Pas de Calais, France (Coppejans *et al*., 1980). Circumstantial evidence suggests that the original transport vector for this species may have been in association with aquaculture of the Pacific oyster (*Magallana gigas*) from Japanese or British Columbian waters (Druel, 1973; Engelen *et al*., 2015). Over the past half a century or so, reports of *S. muticum* in European waters form arguably the most complete record of the geographic spread of an invasive non-native aquatic species (Deysher and Norton, 1982; Critchley *et al*., 1983; Knoepffler-Peguy *et al*., 1985; Rueness, 1989; Harries *et al*., 2007; Kraan, 2008; Engelen *et al*., 2015). Since the 1980s, this species has been recorded in the Atlantic from Morocco to Norway (Rueness, 1989; Aires *et al*., 2022), including the Mediterranean Sea (Engelen *et al*., 2015).

In UK waters, after a few years of apparent containment within the Solent strait, populations of attached *S. muticum* were recorded along the northern and southern coasts of the English Channel (Critchley *et al*., 1983). Since then, the distribution of *S. muticum* has steadily expanded westwards and northwards (Davison, 2009), presumably aided by prevailing wind and current direction driving a clockwise dispersal of propagules and drift fragments (Harries *et al*., 2007). The discovery of attached populations is often preceded by observations of drift or beach-cast specimens (Deysher and Norton, 1982; Critchley *et al*., 1983; Rueness, 1989). By 2004, *S. muticum* was recorded in Scotland (Reynolds, 2004). In 2020, the most northerly UK record of this species attached *in situ* was documented at Tulm Bay on the Isle of Skye (57.69419 N; 6.35647 W) (National Biodiversity Network, 2023b) (Figure 1).

Sargassum muticum in Orkney

In August 2015 at Warbeth, West Mainland (Figure 2), a beach-cast, i.e. not attached to a substrate, individual of *S. muticum* became the first accepted observation of this species recorded in Orkney waters (Derek Mayes, pers. comm., 2015; Kakkonen *et al*., 2019; National Biodiversity Network, 2023c). The first observations of potentially established populations were reported to the Orkney Islands Council Harbour Authority (OICHA) by recreational snorkellers in August 2019 from rock pools in Birsay Bay and in May 2020 at the Choin, Marwick (Alison Moore, pers. comm. 18 May 2020), both locations on West Mainland, Orkney.

Genetic variation of *S. muticum* populations

To understand mechanisms behind NNS spread and to effectively manage them, invasion genetics have frequently been utilised to identify cryptic species and populations and track their origins (Geller *et al*., 2010). For marine NNS, a review of publications carried out in European seas, concluded that three quarters of studies reported similar level of genetic diversity in native and in some or all introduced populations but also highlighted marine species with limited genetic diversity in introduced populations (Rius *et al*., 2015). For *S. muticum*, the traditional ribosomal (ITS2 spacer) or mitochondrial DNA (TrnW_I spacer) markers showed overall low diversity in both native and introduced populations (Cheang *et al*., 2010). Alternatively, the cox3 mitochondrial gene inferred a high genetic diversity in the native range while introduced *S. muticum* populations all belonged to a single haplotype (Bae *et al*., 2013). More recently, with advancements in technology, microsatellite and genome-wide single-nucleotide polymorphisms confirmed significantly lower diversity in the introduced *S. muticum* populations compared to the native ones (Le Cam *et al*., 2019). While analysis of 14 microsatellite loci showed no genetic diversity across both *S. muticum* introduced ranges, including 1269 individuals from nine distinct NE Pacific populations and 37 NE Atlantic populations, the genome-wide RAD-seq locus genotyping revealed three different genetic lineages. The observed genetic variation represents some potential to track origins of *S. muticum* introductions. The study by Le Cam *et al*. (2019) unearthed some hidden diversity within the NE Pacific populations and suggested that the NE Atlantic population of *S. muticum* shares more genetic background with the Southern NE Pacific populations rather than the Northern NE Pacific population as previously thought (Engelen *et al*., 2015).

While *S. muticum* is not listed as one of the high-risk invasive species highlighted in the approved OICHA Ballast Water Management Policy for Scapa Flow (OICHA, 2017), identification

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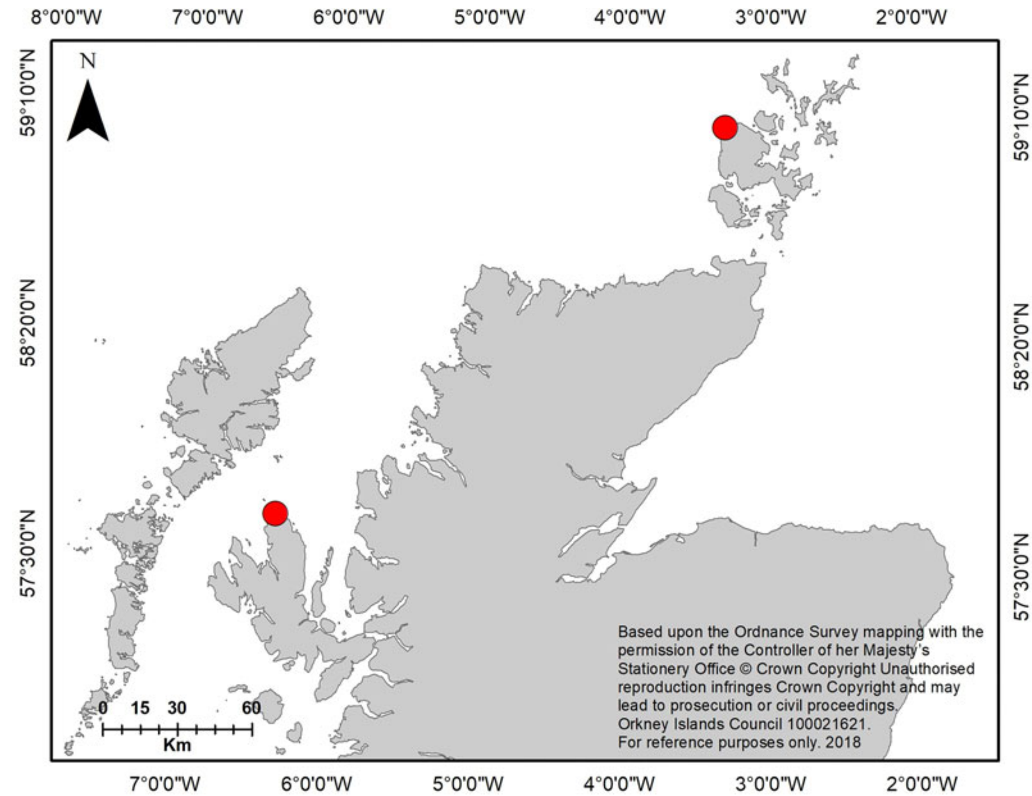

Figure 1. Map of the north of Scotland showing the previous and new records of the most northerly established UK populations of *Sargassum muticum* from Tulm Bay, Skye and Birsay Bay, Orkney.

of the potential arrival of this species has formed part of a monitoring programme continuing in these waters since 1974 (Jones, 1980; Kakkonen, 2019; Kakkonen *et al*., 2019). The present study summarises the outcomes of a focussed investigation to confirm its presence at the Choin and Birsay Bay areas and a possible further spread throughout the Orkney Islands. The secondary aim of this study was to confirm the species identification by use of the cytochrome oxidase subunit I (COI) gene of mitochondrial DNA barcoding. Considering the limited number of samples available for analysis and high costs of genome-wide RAD-seq locus genotyping, invasion genetics-related analyses were outside of the study scope and not included here.

Materials and methods

The OICHA has been monitoring the shores and waters of Scapa Flow and the wider Orkney archipelago since 1974 (Jones, 1980; Kakkonen, 2019). Surveys target 22 rocky and 13 sandy shores, 11 sites for radiological monitoring, and, since 2013, sites are also surveyed for presence of NNS (Atkins *et al*., 1985; Kakkonen, 2019; J. Kakkonen unpublished data). OICHA survey sites are located throughout the Orkney Islands archipelago representing a range of environmental conditions along gradients of exposure, salinity, and pollution, as well as including different substrates (Table 1; Figure 2). Since 2014, rocky shore monitoring by the OICHA has adopted the MarClim survey protocol described by Mieszkowska *et al.* (2005) and utilised as part of long-term monitoring on Scottish shores (Burrows *et al*., 2017). MarClim-style surveys are conducted by a team of two, with one person assigned to take photos and replicate counts of barnacles and limpets while the second person with the aid of survey form identifies and allocates species to a SACFOR abundance scale (Hiscock, 1981). Any noteworthy species, including NNS, are included in the survey forms; species of interest which are not on the checklist are recorded and a SACFOR scale allocated.

A dedicated snorkel survey of the Choin, Marwick (59.09864 N; 3.34949 W) was conducted in summer 2021 with the aim to locate and confirm the identity of purportedly established populations of *S. muticum*. The Choin (Figure 2) is a tidal rocky shore area connected to the open sea by a narrow channel and consists of two large pools extending southwards and northwards. A recreational survey team of two snorkellers (J. Kakkonen and A. Moore) surveyed both main pools. Images were collected and samples taken to the Marine Environmental Unit, Orkney Harbour Authority Building for examination and preservation in 90% ethanol for species barcoding. Additionally, a shore-based survey was conducted, a few kilometres north, along the rocky shores of Birsay Bay (59.13656 N; 3.32593 W) in summer 2022 with the aim to confirm the reported presence of *S. muticum*.

Ethanol-preserved tissue, from two samples of putative *S. muticum*, was homogenised for 2 min at 25 Hz on TissueLyser (Qiagen) using 125 g of glass beads, 450µl of 1% CTAB and 50 µl of Proteinase K and incubated at 56°C for an hour. Genomic DNA was extracted using DNeasy Plant extraction kit (Qiagen), according to the manufacturer's instruction and DNA was eluted in 200 µl AE buffer. A partial fragment of cytochrome oxidase I gene (COI) was amplified using the primers published in Lane *et al.* (2007). Approximately 30 ng of purified PCR product (illustra ExoProStar, VWR) was sequenced using the same primers as in the amplification reaction. Consensus sequences were generated and compared to other sequences deposited in GenBank using BLASTn searches (National Institutes of Health, 2023), with only *Sargassum* spp. sequences published in peer-reviewed literature considered for comparison.

Results

The OICHA's marine NNS monitoring programme has not recorded *S. muticum* during surveys conducted in the last 10 years; more general shore surveys completed since 1974 have

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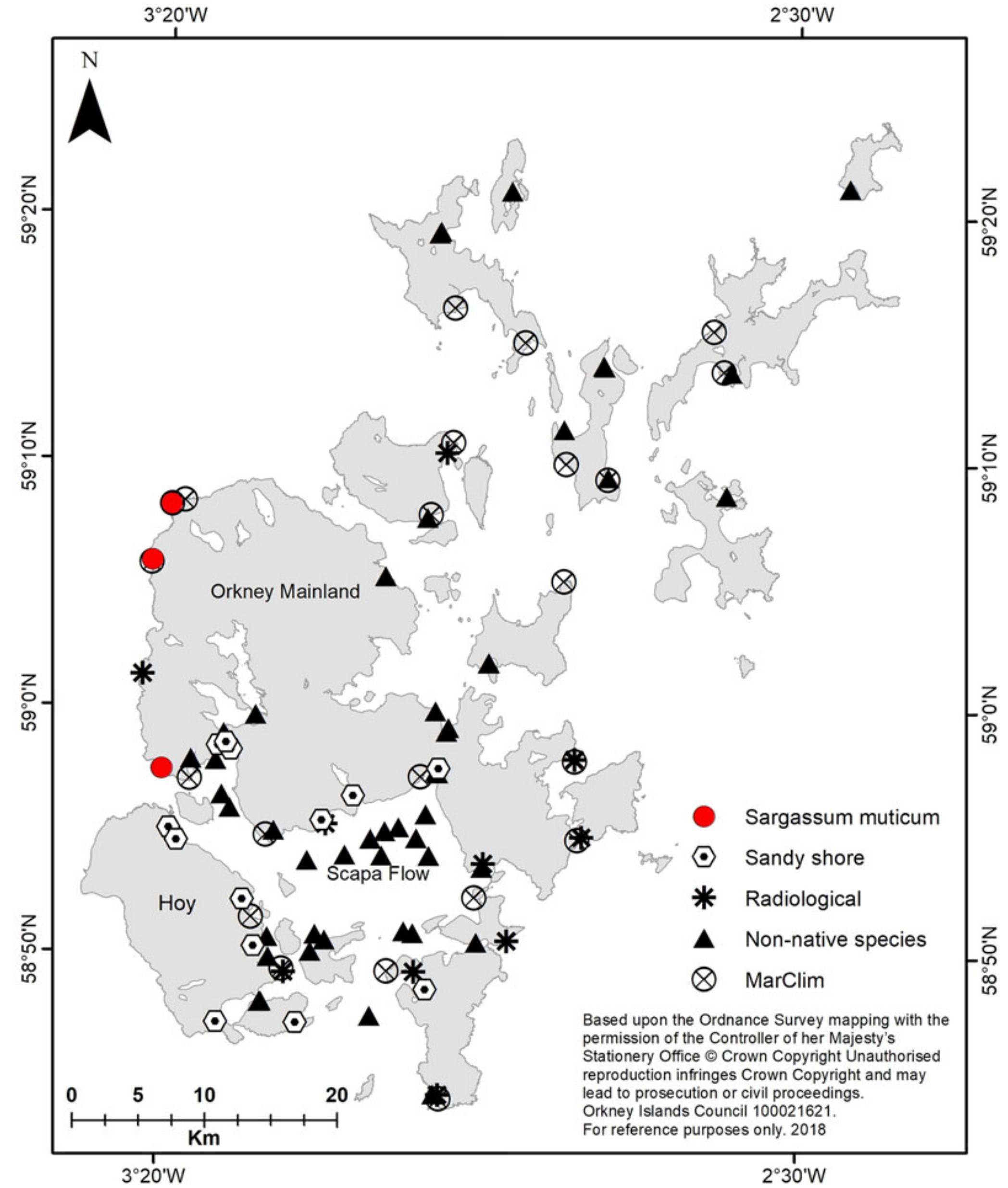

Figure 2. Survey sites monitored by the Orkney Islands Council Harbour Authority. Red dots indicate records of *Sargassum muticum* in Orkney. From the north: Birsay Bay (established population, 2019), the Choin (established population, 2020), and Warbeth Beach (first recorded beach cast specimen, 2015).

not recorded *S. muticum* in the Orkney archipelago (Kakkonen *et al*., 2019; J. Kakkonen unpublished data).

During the 2021 snorkel survey, *S. muticum* was found to be abundant in the northern pool of the Choin. The algae were subtidal amongst native algae, attached to small rocks and had large fronds creating an extensive canopy which was easy to observe (Figure 3). Shore-based surveys identified attached populations with extended canopies in intertidal rock pools in Birsay Bay (Figure 4). Taxonomic guides (Hiscock, 1979; Bunker *et al*., 2017) were used to identify this organism as *S. muticum*; verification was provided by the National Biodiversity Network (2023d).

A PCR product of approximately 700 bp long was amplified from the two algae samples collected. All generated COI gene sequences were identical. Blastn searches of the GenBank database revealed that the generated consensus sequence (588 bp) (GenBank accession number OR051681) for both samples belonged to *S. muticum*. The COI sequences obtained from the Orkney *S. muticum* population were 100% identical to publicly available sequences generated from populations in Norway (MN184280, 84 and MN184364), British Columbia (FJ409213-15) and China (KJ938301).

Discussion

The confirmed establishment of *S. muticum* in Orkney represents a 1.44° (159 km) northwards extension of the latitudinal range of this species in UK waters. The timing of establishment in Orkney in 2019 is consistent with expected spread based on wind, currents, and the earlier discovery of drifted material in 2015 (Rueness, 1989; Stæhr *et al*., 2000; Engelen *et al*., 2015). Beyond the limited observations presented in this study, *S. muticum* has not been recorded at 46 OICHA survey sites, monitored annually since 1974, with attention to NNS since 2013 (Kakkonen *et al*., 2019), providing confidence that the *S. muticum* distribution in Orkney is currently restricted to the west coast of Mainland, Orkney.

The substantial distance between known established populations in Orkney and Skye may be due to several plausible explanations: (i) the remoteness of the northwest Scottish coastline

Table 1. Survey sites monitored by the Orkney Islands Council Harbour Authority

Survey site name	Lat	Long	Survey type	Survey site name	Lat	Long	Survey type
Loch of Stenness sluice gates	58.99527	−3.21072	NNS	Dyke End	58.954038	−2.9933516	MS
Brig O Waithe Bridge	58.98255	−3.25237	NNS	Glimps Holm (3rd barrier)	58.872493	−2.9214406	MS
Bu Point	58.96412	−3.26231	NNS	Holm of Houton	58.913702	−3.1952046	MS
Moaness Pier, Hoy	58.91648	−3.31248	NNS	Banks	59.139022	−3.3080909	MS
Vanguard	58.84706	−3.12895	NNS	Broughness	58.736236	−2.9646944	MS
Gutter Sound	58.84503	−3.19148	NNS	Dingieshowe	58.912183	−2.787677	MS
The Grinds	58.84829	−3.00133	NNS	Hoxa Head	58.822292	−3.034622	MS
STS1	58.90100	−3.09128	NNS	Long Geo	58.965486	−2.7918663	MS
STS2	58.91211	−3.05805	NNS	Marwick	59.09654	−3.3505404	MS
STS3	58.91988	−3.02119	NNS	Point of Ness	58.951053	−3.2962201	MS
STS4	58.90089	−2.98149	NNS	Skipi Geo (Brough of Birsay)	59.136237	−3.3249718	MS
Clestrain Sound	58.94100	−3.25383	NNS	Eday pier, Eday	59.156044	−2.7524292	MS
Scapa Flow (middle)	58.90079	−3.04334	NNS	Sandybank, Eday	59.166262	−2.8072751	MS
Hoxa Sound/Switha Sound	58.79200	−3.05600	NNS	Crockness, Hoy	58.823016	−3.1716977	MS
Kirkwall Marina	58.98769	−2.95795	NNS	Pegal Bay, Hoy	58.857825	−3.2128251	MS
Stromness Marina	58.96478	−3.29453	NNS	Rousay Pier, Rousay	59.131166	−2.984289	MS
Westray Marina	59.32312	−2.97601	NNS	Scockness, Rousay	59.180186	−2.9563367	MS
Buoy 1 Scapa	58.95810	−2.97333	NNS	Kettletoft, Sanday	59.229651	−2.6000	MS
Buoy 2 Holm	58.89333	−2.91200	NNS	Noust of Ayre, Sanday	59.256953	−2.6137054	MS
Buoy 3 Burray	58.84250	−2.91800	NNS	Ness of Ork, Shapinsay	59.08682	−2.8086909	MS
Buoy 4 Longhope	58.80133	−3.19867	NNS	Kirk Taing, Westray	59.271334	−2.955856	MS
Buoy 5 Longhope	58.80084	−3.20000	NNS	Rapness, Westray	59.248366	−2.8627454	MS
Buoy 6 Shapinsay	59.03163	−2.90592	NNS	Congesquoy	58.974059	−3.259391	SS
Buoy 7 Shapinsay	59.03187	−2.90535	NNS	Cumminess	58.971500	−3.242514	SS
Buoy 8 Calf Sound	59.23338	−2.75878	NNS	Scapa Bay	58.960140	−2.970282	SS
Buoy 9 Calf Sound	59.23272	−2.75803	NNS	Swanbister Bay	58.924497	−3.122038	SS
Buoy 10 Eday Pier	59.15762	−2.75150	NNS	Waulkmill Bay	58.941138	−3.081134	SS
Buoy 12 Stronsay	59.14578	−2.59527	NNS	Widewall Bay	58.810393	−2.983909	SS
Buoy 13 Fersness	59.19000	−2.81000	NNS	Dead Sand	58.976332	−3.249037	SS
Buoy 14 Pierowall	59.32200	−2.97773	NNS	Bay of Creekland	58.917787	−3.322620	SS
Buoy 15 Rousay	59.12928	−2.98853	NNS	Kirk Hope	58.787008	−3.152803	SS
Buoy 16 Papa Westray	59.35117	−2.88242	NNS	Longhope Bay	58.786806	−3.256286	SS
Buoy 17 North Ronaldsay	59.35425	−2.43483	NNS	Lyrawa Bay	58.870117	−3.224673	SS
Buoy 18 Kettletoft	59.22927	−2.58991	NNS	Mill Bay	58.838586	−3.209093	SS
The Hurdles	58.93200	−3.24318	NNS	Bay of Quoys	58.909596	−3.312046	SS
SMS Coln	58.89716	−3.14083	NNS	Brough Ness	58.739119	−2.9658799	RM
Royal Oak	58.84950	−3.01283	NNS	Roeberry	58.822438	−2.9990563	RM
Riddock Shoal	58.92913	−2.98579	NNS	Crockness, Hoy	58.821098	−3.1691912	RM
Between STS2 and STS3	58.91743	−3.03971	NNS	Long Geo, Tankerness	58.967031	−2.7918322	RM
Between STS3 and STS4	58.91264	−2.99817	NNS	Bay of Ham, Rousay	59.173283	−2.9643662	RM
Burwick Pier	58.73951	−2.97201	NNS	Swanbister	58.921793	−3.1169136	RM
Houton Pier	58.91715	−3.18506	NNS	Burray, Sea Geo	58.843902	−2.8780669	RM
Kirkwall Pier / Harbour	58.98517	−2.95982	NNS	St Mary's	58.895808	−2.9099258	RM
Scapa Pier	58.95675	−2.97101	NNS	Dingieshowe	58.914573	−2.7817065	RM
Tingwall Pier	59.08954	−3.04269	NNS	Birsay	59.136162	−3.325301	RM
Flotta Piers	58.83535	−3.13470	NNS	Yesnaby	59.021586	−3.3600116	RM

(*Continued*)

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Table 1. (*Continued.*)

Survey site name	Lat	Long	Survey type	Survey site name	Lat	Long	Survey type
Flotta Jetty	58.84325	−3.11652	NNS				
Ore Bay mooring buoy	58.83136	−3.18953	NNS	**Locations *Sargassum muticum* recorded in Orkney**			
Hatston mooring buoy	58.99882	−2.97496	NNS	Choin, Marwick	59.09864	−3.34949	
				Birsay Bay	59.13656	−3.32593	

Non-native species monitoring (NNS); MarClim style rocky shore survey (MRS); sandy shore survey (SS); radiological monitoring (RM).

and the low density of observers may mean that 'stepping-stone' populations exist but remain unknown; (ii) there may be a lack of suitable anthropogenic vectors between locations; and (iii) there may be no suitable habitat in between to allow establishment. The latter view is supported by Harries *et al.* (2007) based on the unsuitably high level of wave exposure on these coasts. However, if the known Orkney sites, which are extremely wave-exposed, are indicative of the habitat of this species in the north of Scotland, its presence along the northwestern and northern coasts might indeed be expected. MarClim studies along these shores in 2014 found no evidence of *S. muticum* (Burrows *et al.*, 2017). Interestingly, there are several records of drift specimens from the southern Outer Hebrides, but no records of attached individuals in the archipelago and no records from Harris and Lewis (Christine Johnson, Outer Hebrides Biological Recording, pers. comm. 2022). In general, the presence of deeper rock pools and other topographic features which reduce wave energy appears to sufficiently mitigate against extreme exposure (Johnson *et al.*, 2003; Want *et al.*, 2023). Owing to the presence of aquaculture facilities and transport links between Orkney and Skye, it seems unlikely that the west coast of Mainland, Orkney – where there are no industrial facilities or substantial vessel infrastructure - would be at greater risk of introduction of *S. muticum* via anthropogenic vectors. Furthermore, in local Orkney areas of far greater industrial activity, e.g. Scapa Flow, as well as aquaculture facilities and marinas north of Skye, *S. muticum* has not been reported. There are two active Pacific oyster (*M. gigas*) farms in Orkney at Skaill Bay, Isle of Westray, and North Bay, Isle of Hoy. Both farms receive their oyster seeds from hatcheries, reducing the possibility of introducing NNS. As part of shellfish production planning process, the Orkney Islands Council requires every site to have a marine NNS biosecurity plan.

The establishment of *S. muticum* in Orkney is of concern to the region from ecological and economic perspectives. On northern and western Scottish coasts featuring suitable habitats, the tendency of *S. muticum* to displace native macroalgae, in particular 'leathery' species of the genera *Fucus*, *Laminaria*, *Bifurcaria*, *Codium*, and *Halidrys* (Viejo, 1997; Stæhr *et al.*, 2000; Sanchez and Fernandez, 2018), may place key species at risk. The fucoid *Halidrys siliquosa* is typically found in deeper, rock pools on West Mainland, Orkney (Want, 2017) and it has been speculated that region-wide replacement of this species by *S. muticum* is possible (Stæhr *et al.*, 2000; Arenas *et al.*, 2003; Engelen *et al.*, 2003). Regional Scottish waters are also home to protected beds of seagrass (James, 2004; Thomson *et al.*, 2014; Kent *et al.*, 2021) vulnerable to replacement by *S. muticum* (den Hartog, 1997; Kraan, 2008). *Zostera marina* may aid colonisation by *S. muticum* by trapping drift fragments, providing a suitable substrate for attachment (Tweedley, 2008). Natural transport of floating *S. muticum* also poses a continuing risk of introducing NNS attached to drifting fragments (Lützen, 1998). Recently discovered invasive species in Orkney, such as *Styela clava*, could have arrived in this manner (Want and Kakkonen, 2021).

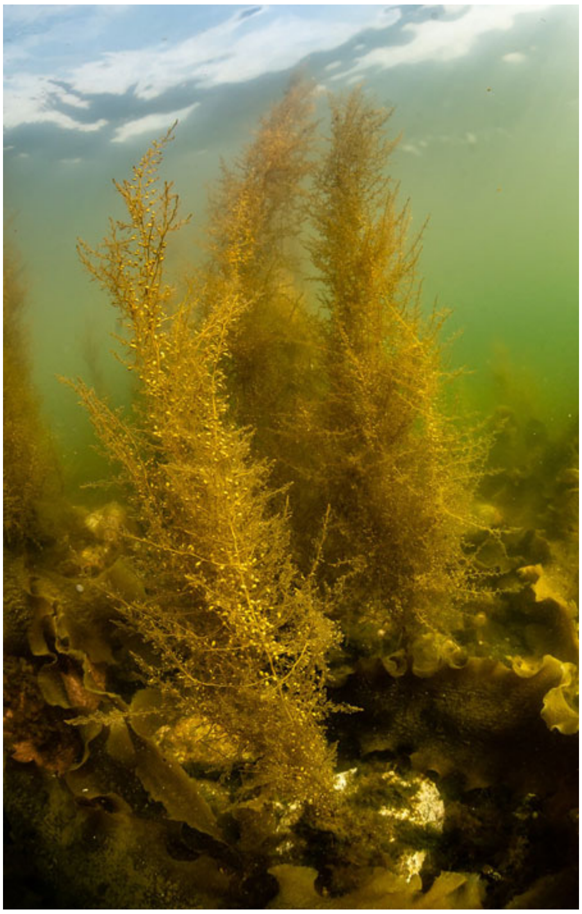

Figure 3. *In situ* population of *Sargassum muticum* from rock pool at the Choin, West Mainland, Orkney (Image: Alison Moore).

Figure 4. Detail of *Sargassum muticum* sampled from Birsay Bay, West Mainland, Orkney (Image: Andrew Want).

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From an economic perspective, areas with thriving fishing and aquaculture industries (e.g. salmon and shellfish farming), such as the west and north of Scotland, the fouling from *S. muticum* may have substantial economic impacts (Harries *et al.*, 2007). Offshore renewable energy devices and infrastructure deployed in these waters provide artificial hard substrate for epibenthic organisms, including macroalgae, which may negatively affect performance and survivability of these technologies (Want *et al.*, 2017). Unsightly masses of floating seaweed may pose a nuisance impactful to local economies, especially in areas dependent on tourism and recreational marine activities (Eno *et al.*, 1997).

In the northeast Atlantic, estimates of spread rate for *S. muticum* range from 15–17 km yr^{-1} (Stæhr *et al.*, 2000) to 69 km yr^{-1} (Mineur *et al.*, 2010). In the studies reported here, confirmed established records in Skye and Orkney are separated by a minimum sea distance of roughly 250 km and 9 years between observations. This represents a spread rate of approximate 28 km yr^{-1}, consistent with existing estimates. The current results and estimate of spread rate may be of value to monitoring programmes in adjacent marine regions, i.e. Shetland and Caithness (Collin *et al.*, 2015; Vawdrey, 2021).

Somewhat unexpected is that the first known establishments in Orkney are recorded from the West Mainland, an area typically characterised by extreme wave exposure (Want *et al.*, 2017) and considered unsuitable for this species (Viejo *et al.*, 1995; Harries *et al.*, 2007). However, the presence of rock pools on gently sloped shores in areas forming (relative) embayments may mitigate against the most destabilising wave forces (Burrows *et al.*, 2008; Want, 2017) and thus may provide suitable substrate for *S. muticum*. Rock pools on West Mainland, Orkney are indeed colonised by relatively lower exposure macroalgae (e.g. *Fucus serratus*, *H. siliquosa*) in close proximity (within 100s of metres) to extreme exposure adapted species (e.g. *Fucus distichus anceps*, *Fucus spiralis nanus*) (Want, 2017). High wave exposure may prevent the survival of *S. muticum* in the shallow sublittoral zones adjacent to the rock pool populations on West Mainland, Orkney.

The traditional COI barcode was generated in this study to accompany the morphological identification of *S. muticum* found in Orkney. The generated COI sequence was identical to sequences of *S. muticum* collected from East Asia (Liu and Pang, 2016) and both NE Pacific (McDevit and Saunders, 2009) and NE Atlantic populations (Bringloe *et al.*, 2019), respectively. Such genetic homogeneity in the introduced populations of *S. muticum* is common and reflects outcomes from other barcoding genes (Cheang *et al.*, 2010; Bae *et al.*, 2013). However, more extensive sampling and RAD-seq genome-wide genotyping is necessary to fully characterise the genetic composition of the Orkney *S. muticum* population.

Conclusion

Establishment of *S. muticum* in Orkney, preceded by the discovery of drift specimens, closely follows predicted patterns of range expansion. Questions remain regarding the observed ability of *S. muticum* to survive adjacent to extremely exposed rocky shores and the lack of records between Skye and Orkney. A focussed survey programme to examine suitable shores in this hard-to-access region would be valuable in helping understand the local habitats and distribution patterns of *S. muticum*. Continued monitoring by the OICHA is an invaluable tool within Orkney waters. Similar programmes in Shetland (Collins *et al.*, 2015) and other parts of the UK may be interested in these results. Rising sea temperatures, associated with global climatic change, suggest that this species will continue to spread northwards (Stachowicz *et al.*, 2002; Engelen *et al.*, 2015) and into cooler waters along the North Sea coast.

Reactive surveys, described in this study as part of ongoing long-term monitoring, are a vital component of biosecurity surveys tasked with early detection of invasive NNS. The spread of invasive NNS is a serious concern to local ecosystems and economies. Eradication programmes are costly and are most effective following a rapid management action plan (Sambrook *et al.*, 2014). As *S. muticum* is not one of the high-risk invasive NNS highlighted in the OICHA Ballast Water Management Policy, there are no current plans to eradicate this species locally. Early detection may be enhanced through application of DNA-based monitoring approaches such as detection of environmental DNA, shed by living organisms into aquatic environment. In last five years, eDNA-based monitoring, either with use of the targeted species-specific real-time PCR assays (for example: Wood *et al.*, 2019; LeBlanc *et al.*, 2020) or metabarcoding approaches and generic COI gene primers (for example: Couton *et al.*, 2019, 2022; Holman *et al.*, 2019), has been applied more frequently to monitor a wide range of marine NNS. The availability of the COI barcode for *S. muticum* can facilitate the development of eDNA-based surveillance for *S. muticum* in Orkney and elsewhere in a similar way as demonstrated for another marine invasive species, *Didemnum vexillum* (Matejusova *et al.*, 2021).

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