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The seaweed resources of Ireland: a twenty-first century perspective

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Abstract
The harvesting of wild seaweeds continues to play an important cultural and socioeconomic role for many coastal communities on Ireland's Atlantic seaboard. Although Irish waters contain a diverse and substantial benthic seaweed flora, only a few species are exploited commercially. Historically in Ireland, seaweed was commercially used as a raw material in the production of high-volume, low-value commodities such as animal feed and raw material for alginate production. Recently, with increasing acceptance of seaweed as a sea vegetable and its ever-increasing role as a raw material in the cosmetic and pharmaceutical industries, there has been a renewed vigour in the Irish seaweed industry particularly with new entrants into the human nutrition and cosmetic markets producing high-quality, high-value products. Although many of Ireland's native seaweed species can be sustainably exploited if well managed, the fucoid *Ascophyllum nodosum* maintained its prominent role in the Irish seaweed industry. The traditional harvesting of *A. nodosum* in Ireland continues, although the recent introduction of new harvesting techniques, along with the expected expansion of the Irish seaweed cultivation sector, undoubtedly marks a shift in the Irish seaweed seascape. We focus here on the seaweed resources in Irish waters and how the industry has changed in the last 20 years.

Keywords Seaweed resources · Ireland · Seaweed harvesting · *Ascophyllum nodosum* · Kelp

Introduction

The classic folkloric account of the shores of Connemara, *Cladaigh Chonamara*, Séamas Mac Con Iomaire (1938), originally published in Irish, attempted to "bury the myth that the people of Ireland were a race of thalassophobes incapable of observing their natural surroundings" by describing the diverse marine flora and fauna and the coastal traditions of the west of Ireland. The collection and harvesting of seaweed is an historic practice that remains an important activity both culturally and socioeconomically particularly along Ireland's western seaboard. The practice of collecting seaweed or *ag baint feamainne* provides a supplementary income to harvesters (Macken-Walsh 2009; Morrissey and O'Donoghue 2012), and it has supported a native industry for almost 300 years in Ireland (Hession et al. 1998).

The seaweed biodiversity in Irish waters is considerable, with only 76 fewer recorded species of seaweed than Britain, with a comparatively much smaller coastline (Guiry 2012). A systematic catalogue of the Irish seaweed species referred to as the Rhodophyta, Chlorophyta, and Ochrophyta was produced by Guiry (2012), who recorded some 570 species of benthic seaweed native to Irish waters, of which 161 were Phaeophyceae, 303 Rhodophyceae and 93 Chlorophyceae together with 13 species of *Vaucheria* (Xanthophyceae). A healthy 7.5% of the world's known seaweeds have been reported from Irish waters (Guiry 2012).

Ireland's Atlantic coast has the most diversity of Irish seaweed species (Morrissey et al. 2001), and the lowest biodiversity is found on shores bordering the Irish Sea due to a range of physical, geomorphological, and anthropic factors resulting in unsuitable conditions for the establishment of large seaweed assemblages (Rae et al. 2013). Ireland's shores, except for a few restricted areas in the vicinity of the few large cities, are still relatively pristine (Morrison et al. 2008).

Although Irish shorelines contain a very diverse seaweed flora, only a very limited number of species have economic and/or cultural importance (e.g. *Chondrus crispus* Stackhouse and *Palmaria palmata* (Linnaeus) F.Weber & D.Mohr, amongst others). We here provide an update on the seaweed resources of Ireland, with a focus on the most commercially important species. We examine how the Irish industry has changed over the last two decades and what developments

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are required to make full use of Irish seaweed resources and to further expand the Irish seaweed industry.

Ascophyllum nodosum: Ireland's most commercially important seaweed species

Seaweed processing in Ireland has been relatively stable for the past two decades, allowing Ireland to remain one of Europe's largest producers of seaweed. Since 1966, the Irish seaweed industry has been mostly reliant on the harvesting of *Ascophyllum nodosum* (Linnaeus) Le Jolis (*Feamainn bhuí*), following the cessation of the drying for export of sea rods (*Laminaria hyperborea* (Gunnerus) Foslie) in Ireland which had occurred from 1948 to 1965 (Guiry and Morrison 2013). All *A. nodosum* harvesting occurs sustainably from wild stocks, with most material cut by hand using traditional techniques (Mac Monagail et al. 2017). In 1999, *A. nodosum* accounted for 94% of the total Irish seaweed landings. In 2016, the proportion grew marginally to 95%, highlighting the continued fundamental role *A. nodosum* plays in the Irish seaweed industry.

In 1999, 36,100 t of *A. nodosum* were harvested in Ireland, equal to 10.5% of total European seaweed production. In 2016, the tonnage landed in Ireland was 29,500 t, equivalent to 11% of the overall European seaweed market (FAO 2018). Harvested seaweed was virtually all from the wild harvest, making Ireland the third most productive country in Europe, behind Norway and France (Table 1) (FAO 2018).

Harvesting of *Ascophyllum nodosum*

Some 75% of landed biomass harvested of *Ascophyllum* is from counties Galway, Mayo and Donegal (Fig. 1), with smaller amounts from counties Sligo, Clare and Kerry. Several harvesting techniques are now employed by the harvesters of Ireland, depending on local conditions and tradition. When harvesting *A. nodosum* in Connemara, for example, harvesters cut seaweed (Fig. 2a) at low tide using a sickle or a small sharpened knife, referred to as a *corrán* (literally a crescent) or a *scian bheag* (little knife). The harvested material is placed upon two crossed ropes, which are used to tie the stack of seaweed in place into a 2 to 4-t *climín* (literally a bundle, plural cliníní) (Fig. 2b). The *climín* is then allowed to float with the incoming tide and is usually towed to the nearest pier using a traditional boat (*currach*) from where it is transported for processing by lorry (Fig. 2c). In counties, Clare and south Galway, the use of a flat *climín* or a *téad* (literally a rope) (Fig. 2d) is more common than the use of *cliníní* when harvesting *A. nodosum* due to the nature of the shoreline. Depending on their experience and skills, seaweed harvesters are typically capable of cutting between 1 and 4 t in a single tide cycle, although it has been known for some cutters to harvest as much as 7 t on a good tide.

After cutting, beds are left fallow for 3–7 years to allow regeneration depending on the harvesters' local knowledge and experience. In counties Galway and Donegal, this period is generally between 3 and 4 years, while in Co. Mayo, it can be between 5 and 7 years. This practice was recorded by the Norwegian researcher Egil Baardseth while working in the west of Ireland, who reported the opinion of cutters that recently harvested areas of *A. nodosum* should fallow for a period of "3–6 years" to allow the seaweed to recover properly. Recovery also depends on the exploitation rate and the amount of actively growing shoots remaining (Baardseth 1955, 1970). There are also significant economic benefits associated with sustainable harvesting and allowing adequate recovery times (Rebours et al. 2014). The self-imposed implementation of fallow periods following harvest ensures the recovery of seaweed beds and allows for a well maintained and sustainably exploited resource (Morrissey et al. 2001).

Table 1 Top European producers of wild seaweed

Country	Species	Tonnage
Norway	Aquatic plants, Brown seaweeds, Rockweed	169,407
France	Brown seaweeds, North European Kelp, Tangle	55,041
Ireland	*North Atlantic rockweed, North European kelp, Red seaweeds*	*29,500*
Iceland	Rockweed, North European Kelp, Tangle	17,985
Russian Federation	Aquatic plants, Brown seaweeds, North European kelp, red seaweeds	14,022
Spain	Brown seaweeds, Gelidium seaweeds, Green seaweeds, Ribboned nori, Wakame	3493
Portugal	Red seaweeds	2328
Italy	Green seaweeds, Red seaweeds	1200
Estonia	Red seaweeds	348

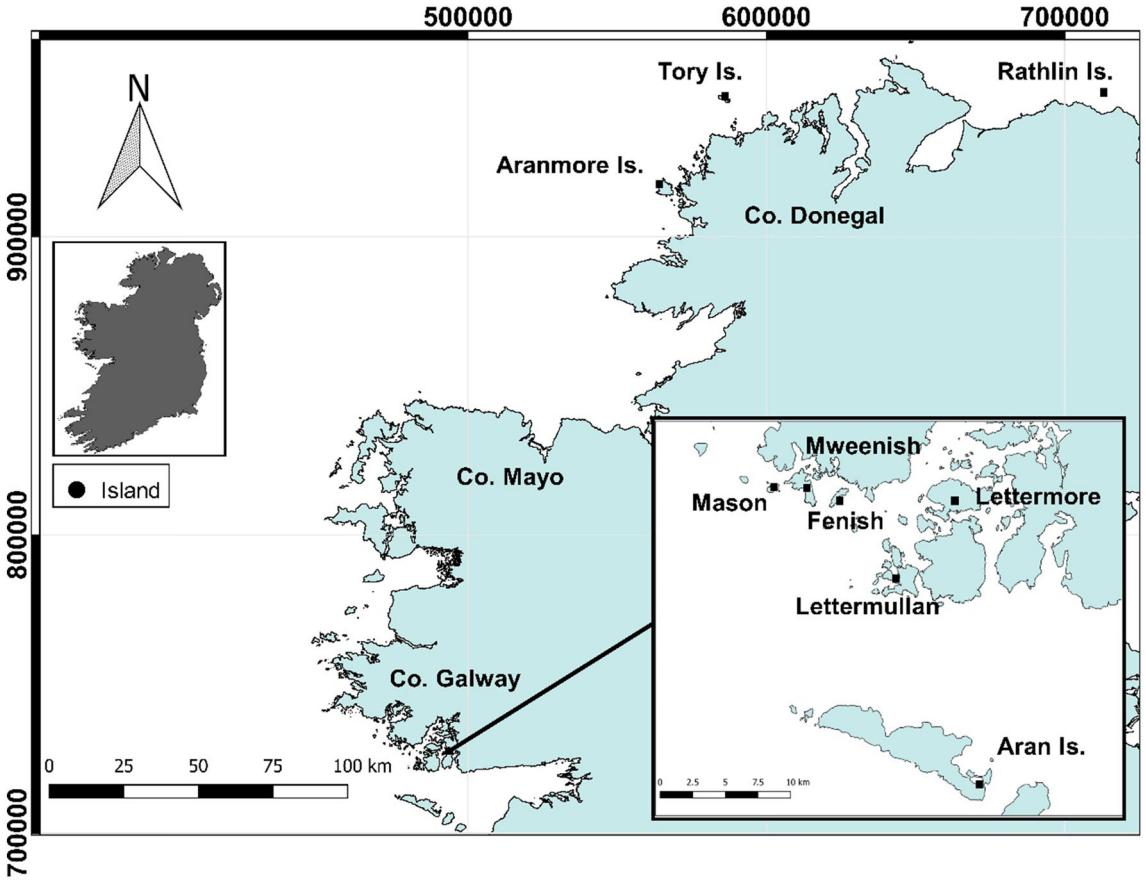

Fig. 1 Map of Ireland showing locations of seaweed harvesting mentioned in the text

Laminaria hyperborea

Important kelps in Irish waters include *L. hyperborea*, of which 1400 wet tonnes are harvested from wild stocks in 2016 (FAO 2018). The harvesting from wild stocks of this kelp occurs mostly in the southern counties of Cork and Kerry (Buschmann et al. 2017).

The harvesting of "sea rods" (*L. hyperborea*/*slataí mara*/*budógaí*) played a meaningful role for Irish coastal inhabitants from the mid-eighteenth century for about 100 years. The manufacture of "kelp" from seaweed was a profitable undertaking for many island residents in the north and northeast of the country, particularly in areas such as Aranmore Island, Tory Island and Rathlin Island (Fig. 1), where it is said that "persons of every age and sex [were] employed collecting seaweed, or carrying it off the beach on the small island horses" (Forde 1926; Forsythe 2006). In Ireland, it was the progress of the bleaching trade that created a demand for alkali (Clow and Clow 1947). In the west of the country, on the Aran Islands and the islands of Lettermullan, Lettermore, Mweenish, Fenish and Mason, inhabitants took advantage of kelp burning and the use of "black weed" harvested and brought from the shore in "back loads" by "the women who join in all fieldwork, and seem to be the hardest worked members of the community" (Browne 1900).

Rhodophyta

Of the Rhodophyta, some native species, including *P. palmata*, *Chondrus crispus*, *Mastocarpus stellatus* (Stackhouse) Guiry and the coralline red algae collectively referred to as maerl, have historically been utilised by coastal communities, either as a food source (Mouritsen et al. 2013) or as a source of fertiliser (as in the case of maerl; O'Reilly et al. 2012). According to FAO (2018), "red seaweeds" accounted for < 0.5% of the total national landings by volume (approximately 100 t) in Ireland (Table 2). Both *C. crispus* and *M. stellatus* are important carrageenophytes (Necas and Bartosikova 2013) and are harvested at low tide by plucking or cutting the small plants from the lower intertidal using either a sharpened small knife or scissors. Irish harvesters collect both seaweeds indiscriminately as carrageen (*carraigín*). Most harvesting occurs during the autumnal equinoctial spring tides (Pybus 1977). The harvesting of the delectable alga *P. palmata* (Dulse or Dillisk) occurs on only a

Fig. 2 **a** Traditional hand harvesting of *A. nodosum* on the west coast of Ireland. **b** *Climiní* stored on local piers awaiting collection and transportation to *A. nodosum* processing factory. **c** Traditional *Climiní* being tower ashore at high water, Co. Galway. **d** Flat *Climín* (rings) being towed ashore in Co. Donegal

small scale throughout the Atlantic coast of Ireland (Edwards and Dring 2011).

Several species of maerl are present in Irish waters (Fig. 3a), but only two are of current economic importance (*Phymatolithon calcareum* (Pallas) W.H.Adey & D.L.McKibbin ex Woelkering & L.M.Irvine and *Lithothamnion corallioides* (P.Crouan & H.Crouan) P.Crouan & H.Crouan). Sizeable deposits of both occur at more than 60 locations along the west coast of Ireland (De Grave et al. 2000). Maerl is also found washed up on shores known as "coral strands" (Guiry and Hession 1998), such as *Trá an Dóilín* near Carraroe, Co. Galway and Mannin Bay, Co. Galway.

The gathering of drift weed or storm cast material (*racálach*) (Fig. 3b) from the upper part of the beach was historically an essential source of raw material as a soil treatment or as an additive for animal feed (Guiry and Morrison 2013). This resource was seen as a readily available source of biomass, the right of which to gather in particular areas was given to the first family down to the shore in the morning (O'Neill 1970). In recent years, however, and as a response to industry demands for improved quality of raw material, the gathering of cast weed has almost disappeared except for personal use.

Table 2 Irish seaweed landings 2016 (FAO 2018)

Species	Tonnage landed
North Atlantic rockweed	28,000
North European kelp	1400
Red seaweeds	100

Introduction of new harvest techniques

Although to date the Irish seaweed industry has been wholly reliant on traditional hand harvesting, some new harvest methodologies are beginning to emerge in Ireland to augment traditional hand harvesting, particularly using rakes from boats for *Ascophyllum* and the use of mechanical harvesting for kelps.

Hand-harvesting into a boat

Though the practice of harvesters cutting seaweed using a *croisín* (a pole with a hook and crosspiece for harvesting seaweed) into a traditional *currach* or *húicéir* boat has occurred in the past, increasing water safety regulations in Ireland has curtailed these practices.

Following its introduction into the Canadian Maritimes in the 1960s (Chopin and Ugarte 2006), the boat and rake

Fig. 3 **a** Maerl. **b** Storm cast kelp rods, Co. Mayo. **c**, **d** Newly adopted boat and rake harvesting technique, Co. Galway

method for commercial *A. nodosum* harvesting was introduced in Ireland in 2016. Purpose-built boats are operated by experienced harvesters, while specially designed rake heads produce minimum changes to the habitat architecture following harvest (Ugarte et al. 2006) (Fig. 3c, d). This harvest method also allows individuals to take advantage of the rising tide offering improved socio-economic opportunities for harvesters. Due to several factors, however, including the slope of the shoreline, the geomorphology of the area, and the experience and skills of harvesters working in difficult conditions, the traditional hand-harvest is still the only viable harvest option in many areas. The boat and rake harvest method has provided to date only a limited amount of biomass to the industry in Ireland.

Mechanical harvesting

The mechanical harvesting of Irish seaweed resources, for both *A. nodosum* and kelps, has previously been identified as a key area of development for the domestic seaweed industry (Werner and Kraan 2004). In recent years, the proposed introduction of mechanical harvesting methods in Ireland has attracted considerable interest, from both the industry and from local communities (Baker 2017; Roseingrave 2017).

Mechanical harvesting of seaweeds is carried out in some parts of Europe (Kadam et al. 2015), particularly in northern European countries such as Iceland and Norway which are at the forefront of developing mechanical harvesting techniques (Tiwari and Troy 2015). Mechanical harvesting provides the vast majority of Norway's national seaweed output (Meland and Rebours 2012), with seaweed trawlers operated for the harvest of *L. hyperborea* capable of harvesting 50–150 t day^{-1} (Vea and Ask 2011). Smaller paddle wheel cutters are operated for the *A. nodosum* harvest (Meland and Rebours 2012). In Iceland, *A. nodosum* is harvested using mechanical harvesters equipped with adjustable rotating cutting blades and a conveyor platform which feeds chopped material into net bags (Gunnarsdóttir 2017). In Brittany, depending on the species, the harvesting of kelp is either carried out by boat with gear called "scoubidou" which is used to uproot the kelp or by using large rake-like devices which are dragged through seaweed beds where the larger kelps are uprooted (Mesnildrey et al. 2012). Maerl meanwhile is harvested mechanically in some parts of Brittany using a "sablier" suction dredge which removes the calcareous algae from the sea bottom (Mesnildrey et al. 2012).

Several mechanical harvesters operated in the Canadian Maritimes between the years 1976 and 1990. Older, less efficient mechanical harvesters consisting of a reciprocating cutter mounted on a paddlewheel driven barge (Ugarte and Sharp 2001) were replaced in 1985 by ultra-efficient Norwegian suction cutter harvesters which were capable of harvesting 33.6 wet t day^{-1} of *A. nodosum* (Sharp et al. 1994). Since 1993, harvesting has reverted to boat and rake methods in southwestern Nova Scotia (Chopin and Ugarte 2006).

Mechanical harvesting has the potential to present challenges for fisheries management in terms of protecting marine biodiversity (Kelly 2005). An understanding of the impact of mechanical harvesting on the harvester population is crucial in determining the correct management strategy (Ang et al. 1993). Examples of successfully implemented management strategies exist in Europe. In Norway, a sustainable management program for the harvest of *L. hyperborea* has been in place for 60 years which is based on a clear understanding of the ecology and life cycle of the kelp as well as the ecosystem (Vea and Ask 2011).

The National Parks and Wildlife Service (NPWS) at the Department of Culture, Heritage, and the Gaeltacht in Ireland are responsible for the conservation and protection of Ireland's seaweed resources and for advising the licensing authority (Marine Section within the Department of Housing Planning and Local Government) regarding the issuing of harvest licenses to new entrants (Kelly 2005). The NPWS has repeatedly expressed its opposition to kelp mechanical harvesting in Ireland, stating that "… such activities are not compatible with the conservation objectives of and should not be permitted in Natura 2000 sites".

In June 2009, an application was submitted to the licensing authority to harvest mechanically over an area of 1800 acres 5000 t of kelp (*L. hyperborea*) per annum from Bantry Bay, Co. Cork using a purpose-built vessel equipped with a winch, suction pump and cutter. Approval in principle was first granted in 2011 with a licence subject to conditions granted in 2014. However, following local opposition to the plan (Keogh 2018a), a judicial review was secured in May 2018. Separate High Court proceedings were also launched, seeking an order that the harvesting operation should come under the Planning and Development Act 2000 and not just the provisions of the Foreshore Act 1933 (as amended) under which the license was initially granted. That issue was heard in May 2019, and a judgement was handed down on 6 June 2019, with the High Court dismissing the action and finding in favour of the applicant. However, concerning the Judicial Review proceedings, the High Court was of the view on 29 July 2019 that the State's failure to adequately publish notice of plans to grant a license for large-scale mechanical kelp harvesting off Bantry Bay meant that the license had not yet been effectively issued (Sargent 2019). Further hearings were carried out on 8 October 2019, when the High Court heard submissions from the applicant who are a notice party to the proceedings. Judgement is yet to be made. Should the Court confirm its view by way of ruling then it is likely that the Minister will appeal the ruling to the Supreme Court. Therefore, with regard to the Judicial Review proceedings, the matter is still before the Courts and harvesting has yet to commence.

Seaweed harvesters

It is important to note that few people (if any) make their sole income through seaweed harvesting, and very few people officially declare themselves as harvesters (Delaney et al. 2016). Harvesters, or *bainteoirí*, are effectively seen as sole traders not contracted by any one enterprise and who are free to harvest for whom they wish. In some parts of the country, in particular, some areas of Connemara, the harvesting of seaweed is both an income-generating activity and a cultural commodity (Macken-Walsh 2009). Income-generating activities such as seaweed harvesting are not only economically significant in coastal communities but are also seen as crucial for realising "real" rural development (Macken-Walsh 2009). Most commonly, harvesting seaweed is an income-generating activity which complements a diverse range of other activities including fishing or dredging, lobster potting, wall building, small-scale farming, or turf cutting, depending on the time of the year.

The age structure of harvesters in the Connemara region in 1997–1998, as reported by Kelly et al. 2001, was such that 13% of harvesters were under the age of 40, while only 3% were under 30. Twenty years on, and this demographic is still apparent (pers. obs.). Seaweed harvesting is challenging, and labour-intensive work and for the most part the younger generations migrate away from rural coastal areas in search of higher paid employment. The age profile of the average harvester and the difficulty in recruiting the younger generation to harvest seaweed poses a threat to this traditional practice. A paucity of harvesters will likely threaten the ability to ensure raw material supply to the industry in the near future. New (biotechnological applications) or recovered (traditional food) uses of seaweeds, in addition to the increased price of the raw material, may encourage the uptake in this activity in the near future.

Harvester rights and regulations

Some specific regulations such as the EU Council Directive 92/43/EEC of 21 May 1992 exist relating to the conservation of natural habitats and wild fauna and flora. For the most part, however, little regulation exists in Ireland relating to either harvestable seaweed species or allowable harvestable quantities. In Northern Ireland, the Crown Estate issues licenses for the sustainable, commercial harvesting of seaweed from areas of foreshore and seabed under their ownership. In the Republic of Ireland, however, the seabed and the shore below the line of high water at mean tide, and extending outward to twelve nautical miles, are the responsibility of the State under the 1933 Foreshore Act (revised and amended up to 2017). Under the original 1933 Act, persons are prohibited from gathering seaweed material unless in possession of a "foreshore licence" from the relevant Minister, with the result being

that "many people having no foreshore rights must buy the seaweed or go without" (O'Buachalla, 1937). Under this Act, seaweed constitutes "beach material" whether growing or rooted on the seashore or deposited or washed up by the action of waves, winds and tides. A foreshore licence is required from the Minister to remove organic beach material from the foreshore. Therefore, any individuals or companies seeking to harvest wild seaweed are required to first obtain a foreshore licence under Section 3 of the Act.

However, one exception is where traditional rights to harvest seaweed are in place under one's property. These "seaweed rights" or "folio rights", recorded in landowner folios (which include property details, its ownership and any burdens affecting ownership) dating from the breakup of estates under the Land Commission in the 1920s, have historically ensured access to harvest seaweed material adjacent to some coastal properties in the west of Ireland (O'Neill 1970; Mac Monagail et al. 2017). These "traditional rights" have since been rigorously preserved by the Irish State (Dermody 2018).

Traditional harvesters may in some cases have established rights known as profit-à-prendre rights. The Minister may not grant a licence to harvest wild seaweed where such a licence would interfere with either an appurtenant or profit-à-prendre right to take seaweed or where the foreshore is privately owned. Where an appurtenant or profit-à-prendre right exists, the requirement to hold a foreshore licence under the Foreshore Act does not apply to the individual holding the appurtenant or profit-à-prendre rights, although the rights holders still have to comply with the requirements of the Birds and Habitats Directive. In his speech given at the Our Ocean Wealth Summit, in Galway in June 2019, the Minister has stated "... my Department cannot licence seaweed harvesting in an area where there is an existing right to harvest seaweed… existing seaweed rights holders can continue to exercise their right to harvest seaweed and do not require consent under the Foreshore Act". Where the foreshore is privately owned, the provisions of the Foreshore Act do not apply to the taking of seaweed from the foreshore.

Speaking at the Oireachtas (Irish Parliament) in January 2019, the Minister of State for Local Government stated that "it is now necessary for applicants [to] undertake a search of the Land Registry folios in respect of the area of the foreshore for the which they apply to harvest". Some 6500 folios along the west of Ireland have been identified as containing seaweed harvesting rights (Siggins 2018).

Two decades of change and development within the Irish seaweed industry

The Irish seaweed industry has developed from one whose roots can be traced back to the 1930s (Bixler and Porse 2011; Delaney et al. 2016), with commercial seaweed processing beginning in early 1948. By 2020, the Irish seaweed industry is expected to be worth 30 million € (Sea Change 2006).

Ireland's seaweed industry continues to mature and play a fundamental role in the marine and the coastal economy (Morrissey et al. 2011) and is expected to continue to expand (McMahon 2017; Keogh 2018b). Ireland's ocean economy provides employment for 30,176 full-time employees (Vega and Hynes 2017) with an estimated 700 people engaged in the seaweed sector at the end of the twentieth century (Lyons 2000). As these industries are typically based near the coast, the continued expansion of the Irish seaweed industry will likely promote employment opportunities to the 40% of the Irish population who reside within 5 km of the coast (O'Donoghue et al. 2014; CSO 2017).

A new report on "The global status of seaweed production, trade and utilisation" (Ferdouse et al. 2018) which provides an update of the global seaweed market, including production figures from culture and capture, does not, unfortunately, include Ireland. A report "Valuing Irelands Blue Ecosystem Services" valued seaweed harvesting at 4 million € to the Irish economy (Norton et al. 2014).

There appeared to be little development of the seaweed industry in Ireland in the early part of the twenty-first century with most biomass directed towards industrial processes and the commercial value of seaweeds being limited to high volume, low-value products such as animal feeds and alginates (Walsh and Watson 2011; Guiry and Morrison 2013).

Despite an abundant and diverse native resource, only a minimal number of species are exploited commercially (Table 2). However, many Irish producers have found niche markets where purchasers are willing to pay higher prices for these products.

There exists a diverse indigenous seaweed industry within Ireland. Within the past decade, there have been significant shifts in the Irish seaweed landscape. The largest seaweed processor in Ireland is Arramara Teoranta, which has been largely responsible for the development of the seaweed industry in the country (Hession et al. 1998) and is the predominant processor of seaweeds (Walsh and Watson 2011). The company was acquired by the Canadian group Acadian Seaplants Ltd. in 2014. A second Irish processor, Oilean Glas Teo (OGT), a company based in Kilcar, Co. Donegal was founded in 2004 and specialises in the production of a range of *A. nodosum*-based horticultural products for plants and grass, golf courses and playing fields. The company was acquired by the Spanish group TradeCorp Ltd. in 2014.

There are significant burdens associated with raw material procurement, as well as chemical and energy-related costs to seaweed production (Bixler and Porse 2011). Despite this, changing public perception and acceptance of seaweed as a valuable commodity (Mouritsen 2017) have prompted new entrants to the Irish market. Growth in this industry has been

driven mainly by processing products of higher value and, more recently, by price increases in the harvested raw material (Tsakiridis et al. 2019). In the recent past, there has been an increase in the number of seaweed producers and microbusinesses, marketeers and artisanal retailers, specialising in the production and packaging of seaweed raw materials and finished products in Ireland (Delaney et al. 2016). Many of these small enterprises are concentrated on the west coast of Ireland, producing a variety of seaweed-based products for both the domestic and international food, cosmetic and thalassotherapy markets. Some Irish SMEs, such as This Is Seaweed and Voya, based out of counties Dublin and Sligo, respectively, have successfully developed an internationally recognised brand (Keough 2015, 2018b).

In Northern Island, several small companies such as Islander Kelp and the Irish Seaweed Company, both based in Co. Antrim produces food products from wild local resources. Several Connemara-based companies, including the Connemara Seaweed Company Ltd. and Mungo Murphy's Seaweed Ltd., produce products from a range of locally harvested seaweed species, including dulse, carrageen moss and *Sargassum*, for both cosmetic skincare and food markets. Some indigenous organisations, such as Nutramara Ltd. and Aquaceuticals Ltd. (based in Co. Kerry and Co. Galway, respectively), create and commercialise a diverse range of cosmeceutical and food supplement products and formulations for human health from sustainably harvested seaweed. Cybercolloids Ltd., which has been operating in Carrigaline, Co. Cork since 2002, is a company working in the development of high value, seaweed-based flavour ingredients to the food industry (Reis et al. 2016). In Co. Kerry, since 1998, Brandon Bioscience Ltd. has been focused on the development of *A. nodosum*–based products which are used to improve yield and quality of crops. An enterprise based in Co. Clare, Wild Irish Sea Veg, has been operating for over a decade in the production of seaweed products for human consumption and cosmetic markets. In Cork, Irish Seaweed utilises native species such as dulse, kelp, sea lettuce, Irish moss and wild nori (*Porphyra*) into the brewing process of fruit wine (Walsh and Watson 2011). The range and diversity of the Irish seaweed industry highlights the impressive fluidity in which Irish SMEs can dovetail between high-end food, human nutrition and cosmetic markets.

Cultivation of seaweed in Ireland

Seaweed aquaculture is seen as an integral part of the coastal economy in Ireland (Department of Housing Planning and Local Government, 2018) with growth in the Irish seaweed industry likely to result from an expansion of seaweed cultivation in Irish waters (Werner and Kraan 2004). Although likely to be adjusted according to local Irish conditions (Campbell et al. 2019), Irelands favourable climatic conditions and suitable shoreline show considerable potential for cultivation expansion in Irish waters (Werner et al. 2004). As with the majority of Europe, the Irish seaweed cultivation industry is still in its infancy and has yet to reach anywhere near its full potential (Murphy et al. 2013; Jansen et al. 2019). Requiring no fresh water or fertiliser inputs, however, cultivating seaweeds in Ireland can be relatively resource-efficient and possesses a low carbon footprint (Taelman et al. 2015). The first commercial seaweed pilot farm in Ireland was established in 1996 by Sliog'eisc Mhic Dara in Ard Bay (Campbell et al. 2019) for the cultivation of *Asparagopsis armata* Harvey. This venture has since discontinued (Kraan and Barrington 2005). More recently (since 2015), the Daithi O'Murchu Marine Research Station has been granted a seaweed licence to cultivate native marine algae in Bantry Bay, Co. Cork. Production in Ireland, however, remains limited, with total Irish production through cultivation in 2016 some < 50 t (FAO 2018).

The cultivation of a number of seaweeds, including *P. palmata* and *L. digitata*, is required to meet the demand of a number of sectors, including the requirements of abalone and finfish farmers (Schmid et al. 2003; Edwards and Dring 2011; O'Mahoney et al. 2014) and even to provide raw material to establish a seaweed biogas industry in Ireland (Tabassum et al. 2017).

Currently, there are 17 applications submitted to the DAFM for seaweed licences to cultivate and process a range of native species in Ireland (Cadogan 2018). In the south of the country, several enterprises, including Allihies Seafood Ltd., Emerald Seaweed Ltd. and Dingle Bay Seaweed Ltd., have applied for seaweed aquaculture licenses to cultivate a significantly varied range of species, including *Alaria esculenta* (Linnaeus) Greville; *Saccharina latissima* (Linnaeus) C.E.Lane, C.Mayes, Druehl & G.W.Saunders; *Laminaria digitata* (Hudson) J.V.Lamouroux; *P. palmata*; *Porphyra* sp.; *C. crispus*; and *M. stellatus* on long seeded lines. This activity is expected to grow substantially with the granting of further cultivation licenses.

Open sea cultivation can provide an enormous quantity of biomass for several sectors, particularly relevant as demands for contaminant-free seaweed for use in nutraceuticals and pharmaceuticals appears to be increasing (Engle et al. 2018). While wild harvesting can result in variation in the availability and quality of the finished product, and the possibility of heavy metal contamination is a significant issue (Edwards and Dring 2011; Ferdouse et al. 2018), several challenges also exist for the guaranteed supply of seaweed through sustainable cultivation. Biotic and abiotic stressors are significant challenges to global seaweed aquaculture (Ding and Ma 2005; Loureiro et al. 2015) with cultivation very dependent on any outbreak of seaweed disease of pest species (Borlongan et al. 2011). An infestation of epiphytes can result

in considerable quality deterioration (Stévant et al. 2017) with grazing of seaweed tissues by herbivores resulting in inconsistent crop yields (Ganesan et al. 2006). Infestations of the parasitic epiphyte *Polysiphonia* sp. can drastically alter farmed *Kappaphycus alvarezii* (Doty) Doty ex P.C.Silva growth and can even cause farming activity to collapse (Critchley et al. 2004; Tsiresy et al. 2016).

With the further development of new markets in pharmaceutical and human health applications, production of high-quality health and food products with recognised traceability and testable safety standards will be of utmost importance to the successful commercialisation of contaminant-free raw material (Winberg et al. 2011; Hafting et al. 2012). The continued refinement of existing cultivation techniques will likely improve quality control and traceability of products (Hafting et al. 2015).

Seaweed as a source of food in Ireland

One of the goals of the National Marine Research & Innovation Strategy 2017–2021 is the continued contribution of seaweed to Ireland's food production and processing sector, which incidentally is Ireland's largest indigenous industry sector. Until the last decade or so, the consumption of seaweed in Ireland, except in some localised hotspots, appeared to have more or less discontinued. Seaweeds in Ireland were historically regarded as a food source for the poor due in part to the relation to their consumption during the great famine in the 1840s (see for instance Mokyr and O'Gráda, 2002). More recently, however, seaweeds have undergone a renaissance in Ireland, and across Europe, and are now viewed as both a nutritious and versatile food adding taste and mouth-feel to innovative dishes (Mouritsen 2017; Lucas et al. 2019).

Edible seaweed products may be available to consumers in a variety of forms, either fresh or dry, powdered and flaked (Buschmann et al. 2017). The nutritional composition of several edible Irish seaweeds have exceptional potential as valuable commercial food products (Skrzypczyk et al. 2019) holding nutritional and therapeutic promise (MacArtain et al. 2007; Mendez et al. 2019) with many native Irish seaweeds finding a place in the functional food market (Holdt and Kraan 2011; Wells et al. 2017).

Certain seaweeds have specific and diverse sensory characteristics which can provide consumers with a large variety of sensory qualities (Chapman et al. 2015). Only a small number, however, are exploited for human consumption in Ireland. *Palmaria palmata* is considered a food delicacy with much of this edible seaweed harvested and consumed within Ireland (15–30 t) (Walsh and Watson 2011).

Harvested quantities are influenced by market demands as well as seaweed availability (Bixler and Porse 2011) with demand for *P. palmata* as a snack in northern Ireland regularly outstripping supply from natural populations (Edwards and Dring 2011). *Chondrus crispus* is also used as a traditional herbal remedy in some coastal households in the west of Ireland (pers obs.). Barring some limited usage, it would appear that some species, including *Porphyra* and *Pyropia* species (*sleabchán*), have all but fallen out of household use.

Invasive species

The number of introduced seaweed species to Irish waters is relatively small (Guiry 2012; Rae et al. 2013). Many, such as *Asparagopsis armata* (first recorded in 1941 in Galway Bay (De Valera 1942)), *Polysiphonia harveyi* Bailey (first recorded in 1990 by Maggs and Hommersand (1990) and *Codium fragile subsp. tomentosoides*[1] and subsp. *atlanticum* (first recorded in 1941 in 1911, respectively in Ireland) (Parkes 1975; Provan et al. 2008), are now common species throughout Irish waters. A recent arrival to Irish waters is the *Undaria pinnatifida* (Harvey) Suringar that was first recorded on the east coast of Ireland, in Kilmore Quay, Co. Wexford in July 2016 (Kraan 2017). More recently, the presence of *Agarophyton vermiculophyllum* (Ohmi) Gurgel, J.N.Norris & Fredericq (previously *Gracilaria vermiculophylla* (Ohmi) Papenfuss) was confirmed by molecular means in an estuary located in Clonakilty, Co. Cork in 2019 (Bermejo et al., 2019a) while the kelp *Laminaria ochroleuca* Bachelot de la Pylaie has been recorded for the first time in Irish waters in Belmullet, Co. Mayo (Schoenrock et al. 2019).

Invasive seaweeds can be in direct competition with native biota (Hammann et al. 2013), and they have the potential to alter habitat structure (Dijkstra et al. 2017). Some of the chief concerns relate from direct competition with native Irish biota and the potential to alter habitat structure (Stokes et al. 2004; Hammann et al. 2013; Dijkstra et al. 2017).

The first recorded arrival of *Sargassum muticum* (Yendo) Fensholt in Irish waters was documented in Northern Ireland in Strangford Lough, Co. Down, and in the Republic of Ireland in Cashel Bay, Co. Galway, in 1995 and 2001, respectively (Boaden 1995; Loughnane and Stengel 2002), although it most likely occurred in Irish waters a decade before then (Kraan 2008). *Sargassum muticum* has since spread from Co. Donegal (Kraan 2008) to Co. Cork (Salvaterra et al. 2013). It is thought unlikely to cause widespread ecological impacts in Scotland (Harries et al. 2007), with *S. muticum* showing limited impact on native algal assemblages from rocky intertidal shores from Northern Spain (Olabarria et al. 2009), but few studies have been carried out in Ireland to substantiate these opinions, and the impact on native Cystoseiraceae and seagrass beds remains to be assessed. High abundances of *S. muticum* can result in space monopolisation and reduced

[1] Now considered to be *Codium fragile* subsp. *fragile* (Suringar) Hariot

resources for native species (Schaffelke and Hewitt 2007), thus changing the functional behaviour and structure of indigenous seaweed assemblage communities. *Sargassum muticum* may interact and replace native eelgrass and the brown seaweed *Himanthalia elongata* (Linnaeus) S.F.Gray though this effect may be site-specific (Den Hartog 1997; Baer and Stengel 2010). It has been suggested also that this species could have more wide-reaching effects on coastal ecosystems than only direct effects (DeAmicis and Foggo 2015).

The increasing annual proliferation of nuisance *Ulva* spp. blooms in Irish waters is as a result of the enrichment of nutrients and metals in seawater associated with anthropogenic activities (Wan et al. 2017). Some significant and persistent blooms occur annually in a number estuaries in counties Cork, Dublin and Donegal, along with several other counties (Bermejo et al., 2019b).

It can be challenging to define with certainty the transmission pathway of invasive species in Irish waters, with the quantity and quality of invader propagules determining invasion success (Johnston et al. 2009). The spread and transmittance of invasive species in Irish waters may be through several vectors, such as attachment to leisure or fishing vessels (Miller et al. 2007; Vega Fernández et al. 2019) and aquaculture installations (Naylor et al. 2001; Minchin 2007). Marine litter such as floating plastic debris (Rech et al. 2016) can also carry attached alien biota, thereby acting as a gateway for invasive seaweed species (Gregory 2009).

Effect of global change on seaweed biodiversity in Ireland

The threat of climate change to the native flora species biodiversity of Irish waters is inadequately understood with little emerging consensus. Warming Irish waters may result in pressures placed on elements of the native flora and may significantly influence the biodiversity composition of nearshore benthic communities (Harley et al. 2012; Donnelly 2018).

Many kelp species, for example, are negatively affected by ultraviolet radiation, particularly in shallow tidal conditions (Huovinen et al. 2004; Roleda et al. 2006) with projected climate change and warming waters threatening ancient kelp forests in the north Atlantic (Assis et al. 2018). Many cold-water species are likely to be affected by warming waters as sexual reproduction in most kelps will not occur above 20 °C (Dayton et al. 1999) meaning some native kelp species, such as *A. esculenta*, *S. latissima* and *L. hyperborea*, are likely to decrease in abundance and range (Simkanin et al. 2005). As a result of increasing water temperature, a latitudinal retreat in the distribution of some coldwater kelp species such as *A. esculenta* and poleward expansion of warmer water species such as *S. latissima* and *L. digitata* (Merzouk and Johnson 2011) is likely. Climate change will likely affect the standing stock of fucoids in Ireland, with an expected shifting northwards of these species as the North Atlantic warms faster than all other ocean basins (Jueterbock et al. 2013). It has been suggested that increasing water temperatures will likely negatively impact growth rates and therefore canopy cover of *A. nodosum*, with *Fucus vesiculosus* Linnaeus displaying a higher tolerance to warming waters relative to *A. nodosum* (Wilson et al. 2015).

Future scenarios

As laid out in the integrated marine plan for Ireland, "Harnessing Our Ocean Wealth", "ocean wealth will be a key element… generating benefits for all our citizens, supported by coherent policy, planning and regulation, and managed in an integrated manner". It is a challenge to forecast the future of the Irish seaweed industry. Many domestic factors, including an ageing workforce, higher demands from industry for raw material and unpredictable economic conditions, are immediate threats to the industry.

The Irish seaweed industry has always been viewed as having "potential" (Hafting et al. 2015), and it is appropriate that Ireland takes full advantage of its enormously valuable yet underutilised national asset (Shields et al. 2005). It is critical that we improve our fundamental knowledge of biomass quantities and economically significant species to fill knowledge gaps relating to the development of Irelands sustainable bioeconomy (Sánchez et al. 2018).

Many seaweeds native to Ireland, including *A. nodosum*, *L. hyperborea*, *L. digitata*, *P. palmata* and carrageen moss, continue to play vital cultural and industrial roles. The challenges now lie in the further development of cost-effective methodologies to expand the national harvest. Expected industry growth and increasing automation, coupled with higher drying and scaling up capabilities, will likely reduce overheads.

A new report "PEGASUS: Phycomorph European Guidelines for a Sustainable Seaweed Aquaculture" calls for the development, improvement and diversification of seaweed aquaculture practices across Europe (Barbier et al. 2019). Seaweed cultivation if properly managed can help develop underutilised marine resources throughout Europe (Campbell et al. 2019), and consequently, increasing emphasis on seaweed cultivation may allow wild harvesters a diversification opportunity to augment their income and transfer their skills and equipment to other species (Burrows et al. 2018). The large-scale roll-out of cultivation facilities in Irish waters requires thoughtful consideration for the location of cultivation sites.

As the popularity of Irish seaweed products increases along with numerous new entrants into the Irish seaweed market, uninhibited exploitation of a resource will likely lead to

additional stress placed upon the resource. Irish authorities must be vigilant and forward-thinking towards the management of Ireland's seaweed resources as historically most management strategies of natural resources generally occur immediately before imminent collapse or after the evident decline of populations (Vásquez 2008). The effects of climate change and continued invasive seaweed colonisation on the abundance, diversity and range of Irish benthic flora have yet to be fully elucidated. We recommend vigilance with regard to the monitoring of invasive species, such as the possible effects of *A. vermiculophyllum* on native *F. vesiculosus* beds (Hammann et al. 2013) and *L. ochroleuca* competition with native *L. hyperborea* assemblages (Smale et al. 2015).

A fundamental impediment to a growing industry is the guaranteed steady supply of high-quality raw material. As Ireland (and Europe) slowly moves away from the harvesting of wild resources and begins to increasingly utilise cultivated raw material, a shift from low-value commodities such as animal feed towards higher-value products in the cosmetic, functional food, nutraceutical and pharmaceutical markets can be expected. It is highly likely that a cultivation industry needs to be developed in order to compete in these markets and to ensure raw material quality and standardisation.

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