Iodine content in bulk biomass of wild-harvested and cultivated edible seaweeds: Inherent variations determine species-specific daily allowable consumption

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ABSTRACT

This study represents a large-scale investigation into iodine contents in three commercially important and edible seaweed species from the North Atlantic: the brown algae *Saccharina latissima* and *Alaria esculenta*, and the red alga *Palmaria palmata*. Variability among and within species were explored in terms of temporal and spatial variations in addition to biomass source. Mean iodine concentration in bulk seaweed biomass was species-specific: *Saccharina* > *Alaria* > *Palmaria*. Iodine contents of *Saccharina* biomass were similar between years and seasons, but varied significantly between sampling locations and biomass sources. In *Alaria* and *Palmaria*, none of the independent variables examined contributed significantly to the small variations observed. Our data suggest that all three species are rich sources of iodine, and only 32, 283, or 2149 mg dry weight of unprocessed dry biomass of *Saccharina*, *Alaria*, or *Palmaria*, respectively, meets the recommended daily intake levels for most healthy humans.

1. Introduction

Iodine is an essential element required for human health and metabolism. Iodine is mostly acquired through the consumption of foods, which are either naturally rich in iodine or enriched with iodized salt. Natural sources of iodine include seafood (e.g. fish, seaweed and shellfish), dairy products (e.g. milk, yogurt and cheese), eggs, fruits and vegetables grown on iodine-rich soil, and products made from grains (e.g. bread and cereals) (Fuge & Johnson, 2015). The fundamental role of iodine in human health is largely associated with the function of the thyroid hormones thyroxine and triiodothyronine (T4 and T3 respectively). These hormones are required for growth and development; e.g., of the brain and the central nervous system. In humans, they also control the carbohydrate, fat, protein, vitamin and mineral metabolism from the 15th week of gestation (FAO, 2001). The current recommended daily iodine intake (RDI) level, as suggested by WHO,

UNICEF, and ICCIDD, depends on age, gender and health status. General guidelines propose $90 \, \mu g \, day^{-1}$ for infants (first 12 months) and children aged 1–6 years, $120 \, \mu g \, day^{-1}$ for 7–12 year-old children, $150 \, \mu g \, day^{-1}$ for healthy adults (12 + years) and $200 \, \mu g \, day^{-1}$ for pregnant and lactating women (FAO, 2001). An iodine deficient diet may lead to major health concerns such as the dysfunction and/or an enlargement of the thyroid gland. On the other hand, ingestion of iodine at levels above the RDI can also negatively affect human health by, e.g. causing nausea. A thyroid dysfunction upon high iodine exposure can occur in vulnerable people with specific risk factors, including those with pre-existing thyroid conditions, the elderly, fetuses and neonates (Leung & Braverman, 2014). However, there is no current evidence for adverse clinical consequences regrading excess iodine intake in the range of $10–200 \, mg \, day^{-1}$ (FAO, 2001; Leung & Braverman, 2014).

The oceans are the richest source of bioavailable iodine (Fuge &

Johnson, 2015) due to leaching from the upper Earth's crust (Muramatsu & Wedepohl, 1998). In seawater, iodine occurs largely as inorganic iodate (IO_3^-) and iodide (I^-) and total iodine concentrations average at 50–65 µg L^{-1} (Truesdale & Upstill-Goddard, 2003). Many seaweeds have an inherent biological capacity to bioaccumulate iodine (Leblanc et al., 2006; Saenko, Kravtsova, Ivanenko, & Sheludko, 1978); for example, Nitschke and Stengel (2015) showed that kelps and other algae accumulate up to 2000 mg kg^{-1} fresh weight, which represents an accumulation factor of 10^3–10^4. In particular brown seaweeds accumulate iodine by absorbing iodide from seawater as described for *Fucus* and *Laminaria* spp. (e.g. Klemperer, 1957; Küpper et al., 1998), suggesting that these species potentially represent a valuable source of iodine for human consumption. Currently in Japan, the iodine intake ranges from 1 to 3 mg day^{-1}, and is largely due to the daily consumption of edible seaweeds; in fact, the iodine intake by the Japanese populations is among the highest in the world (Zava & Zava, 2011). High levels of iodine intake ranging from 20 to 500 mg day^{-1} have been reported also from some other Asian countries, Africa and North and Latin America and Europe (FAO, 2001), but in these cases they could not solely be attributed to seaweed consumption. As latest statistics indicated that 56.9% of Europeans have an insufficient intake of iodine (Andersson, Takkouche, Egli, Allen, & de Benoist, 2005; WHO, 2007), the routine addition of iodized salt to food is strongly recommended (Dunn, 2003).

Many nutritional and health benefits have been attributed to seaweeds. Aside from being rich in iodine, they are a natural source of other essential minerals and trace elements, vitamins, sugars and amino acids, among others (Holdt & Kraan, 2011). Accordingly, they have been traditionally consumed for centuries in many Asian communities in, e.g., China, Japan, Korea and the Philippines. In Europe and North America, the consumption of seaweeds is limited to communities along the North Atlantic coast in Ireland, Britany, Galicia, Maine and Nova Scotia (Guiry & Blunden, 1991). In the Old Icelandic Grágás (Finsen, 1852) guidelines for the issuance of concession and license to collect and trade Søl (also known as Dulse; *Palmaria palmata*, Rhodophyta) for food in the island is documented since at least the year 961. In the more recent past, Asian dishes (primarily sushi; *Porphyra* and *Pyropia* species, Rhodophyta) were introduced across Western societies and the nutritional and health benefits led to an increased popularity of such foods. A strong surge has arisen among Europeans to consume and utilize seaweeds, in addition to sushi, as food, ingredient and supplement (Chapman, Stevant, & Larssen, 2015; Marfaing, 2017; Mouritsen, et al., 2013; Rioux, Beaulieu, & Turgeon, 2017). Hence, there has been growing interest in the sustainable harvesting of wild biomass and/or the cultivation of various seaweed species for food (Chapman et al., 2015) and animal feed, primarily as an alternative source of protein but also as a supply of minerals including iodine (e.g. Tayyab, Novoa-Garrido, Roleda, Lind, & Weisbjerg, 2016). To meet such increasing demand for biomass, seaweed cultivation is rapidly growing across Europe. *Saccharina latissima*, *Alaria esculenta* (both Phaeophyceae, Ochrophyta), and *Palmaria palmata* are species of high interest that are currently cultivated and/or harvested in Europe (e.g. Edwards & Dring, 2011; Skjermo et al., 2014). Despite some challenges and bottlenecks in the production and processing of cultivated biomass, the opportunities and future perspectives for industrial development of seaweed aquaculture in Norway are positive (Stévant, Rebours, & Chapman, 2017).

Iodine concentration in several seaweeds from Ireland were shown to vary between species (brown, green and red seaweed species) and thallus parts (blade, stipe, holdfast) (Nitschke & Stengel, 2015), while seasonal variation in iodine concentration was reported for some Asian (Hou & Yan, 1998) and European species (Haug & Jensen, 1954). Aside from a study on *Laminaria digitata* (Ar Gall, Küpper, & Kloareg, 2004), there is no recent comprehensive study addressing potential temporal and spatial variations in iodine concentrations of seaweeds of commercial value from the northeastern (NE) Atlantic coast, or indeed in any other parts of the world. Particularly kelps (e.g. *Laminaria*

hyperborea and *L. digitata*) may contain high quantities of iodine (Nitschke & Stengel, 2015), and only a limited consumption of biomass of these species avoids health risks. However, seaweed preparation such as washing, drying, and cooking can readily reduce iodine content (e.g. Lüning & Mortensen, 2015; Nitschke & Stengel, 2016). Moreover, following ingestion and digestion, seaweed iodine may have low bioavailability (< 30%) and moderate bioaccessibility (48–82%) (Domínguez-González, et al., 2017).

This study aimed to investigate the temporal (both seasonal and inter-annual) and spatial (latitudinal and cultivation depth) variations in iodine concentrations of wild-collected and cultivated biomass of three commercially important and edible seaweed species: the brown algae *S. latissima* and *A. esculenta* (Laminariales, Phaeophyceae, Ochrophyta) and the red alga *P. palmata* (Palmariales, Florideophyceae, Rhodophyta). Our study consisted of harvesting and handling of seaweed biomass at medium to large (industrial) scales including drying and milling of bulk biomass, i.e. homogenizing large amounts of algal material as it occurs in industry. Thus, the data presented in this study provide valuable information on seaweed raw biomass intended for the use as source of food, feed and food supplement.

2. Materials and methods

2.1. Seaweed biomass collection and processing

Seaweed species were collected considering the following independent variables:

a. Species: The brown algae *Alaria esculenta* and *Saccharina latissima*, collectively known as kelps, and the red seaweed *Palmaria palmata*, locally called Dulse or Søl; hereafter, *Alaria*, *Saccharina* and *Palmaria*, respectively.

b. Location: two sites in Norway (Bodø and Trondheim), and one site each in Iceland and France.

c. Source: wild-harvested ('wild') and cultivated bulk biomass. Only the kelp species *Alaria* and *Saccharina* were cultivated. Wild biomass was collected in Norway: Trondheimsfjord (Vanvikan), Trondheim (63.551 ˚N, 10.217 ˚E), Skjerstadfjorden, Bodø (67.276 ˚N, 14.570 ˚E) and Iceland: Stykkisholmur, Breidafjördur (65.109 ˚N, 22.772 ˚W). Cultivated biomasses were farmed in Norway: Frøya, Trondheim (63.702 ˚N, 8.872 ˚E) and Morsdalsfjorden (67.069 ˚N, 14.076 ˚E), Sund, Gildeskål and Pleubian, France: at CEVA Seafarm (48.847 ˚N, 3.047 ˚W). Cultivation were either monoculture (France and Norway) or integrated multitrophic aquaculture (IMTA) system (Norway only).

d. Season: spring (April and/or May), summer (June and/or August) and fall (September and/or October).

e. Year: 2015 and 2016.

f. Thallus age: young and old sporophytes. Only 2016-harvested lifestages of wild *Alaria* and *Saccharina* were investigated.

g. Cultivation depth: 2, 5 and 8 m. Only 2016 harvest of cultivated *Saccharina* was investigated.

Biomass collection, handling and processing were standardized across sampling locations. Bulk seaweed biomass was collected including the blades, stipes, holdfasts, and sporophylls (specific to *Alaria*). Biomass of *Palmaria* was a mixture of male gametophytes and sporophytes while kelp biomass consisted only of sporophytes. Vegetative and reproductive materials were not separated. Large-scale harvesting of cultivated kelps from ropes may lead to partial loss of some holdfasts. At least 1 kg wet biomass was collected per species: this constitute at least 5–10 adult kelp sporophytes or 50–100 juvenile kelp sporophytes and at least 300 individuals of *Palmaria*. Samples were kept moist, cool and dark during transport. In the laboratory, materials were kept in flowing ambient seawater temperature (season dependent) during processing. Thalli were thoroughly cleaned of associated epiphytes,
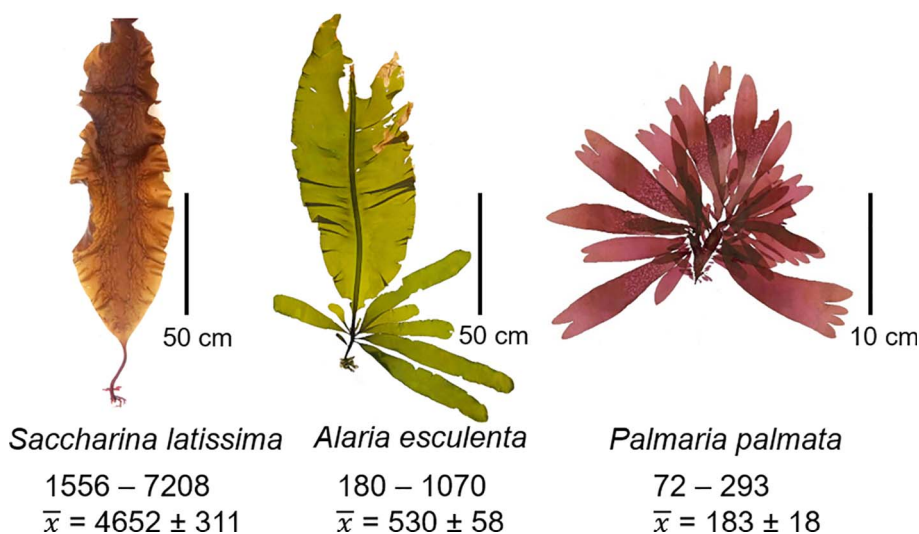
Fig. 1. Species-specific differences in iodine contents ($\mu g\,g^{-1}$ dw). Values are ranges (minimum and maximum), means ± s.e. of all samples collected. Statistical analysis showed significant difference between species (Kruskal-Wallis H test: $\chi^2_2 = 48.709$, $P < 0.001$; *Saccharina* ($n = 27$) > *Alaria* ($n = 22$) > *Palmaria* ($n = 11$)); data are given in Table S1 (Supplementary material). Images are copyright Michael Y. Roleda.

invertebrates, and calcareous particles in a seawater bath within 2 h after collection. Cleaned biomass was swiftly washed in decreasing salinity (100%, 50%, 0%) and immediately drained of excess water, then packed and frozen at −80 °C. Thereafter, samples were freeze-dried and ground to 120 μm grain size. The pooled homogenized biomass was then analyzed in triplicates for total iodine content.

2.2. Analysis of total iodine content of algae

Iodine in dried and homogenized macroalgal biomass was determined according to Nitschke and Stengel (2015). Instrumentation,

reagents, and methodological and technical specifications are outlined in detail in Nitschke and Stengel (2015). All reagents were of analytical or HPLC grade. Briefly, algal iodine was extracted by dry alkaline incineration: a process that converts all inorganic and organic iodine species to I^- ions. This extraction and conversion procedure was conducted by incinerating algal material (< 200 mg) for 4 h at 600 °C in the presence of 17 M KOH. The ash was reconstituted in 2.5 mL of deionized water (18.2 MΩ cm), to which 2.5 mL of methanol were added. I^- in reconstituted ashes (as a measure of total iodine in algae) was quantified using a HPLC system (1200 Series, Agilent Technologies, Palo Alto, USA). I^- ions were separated from interfering compounds
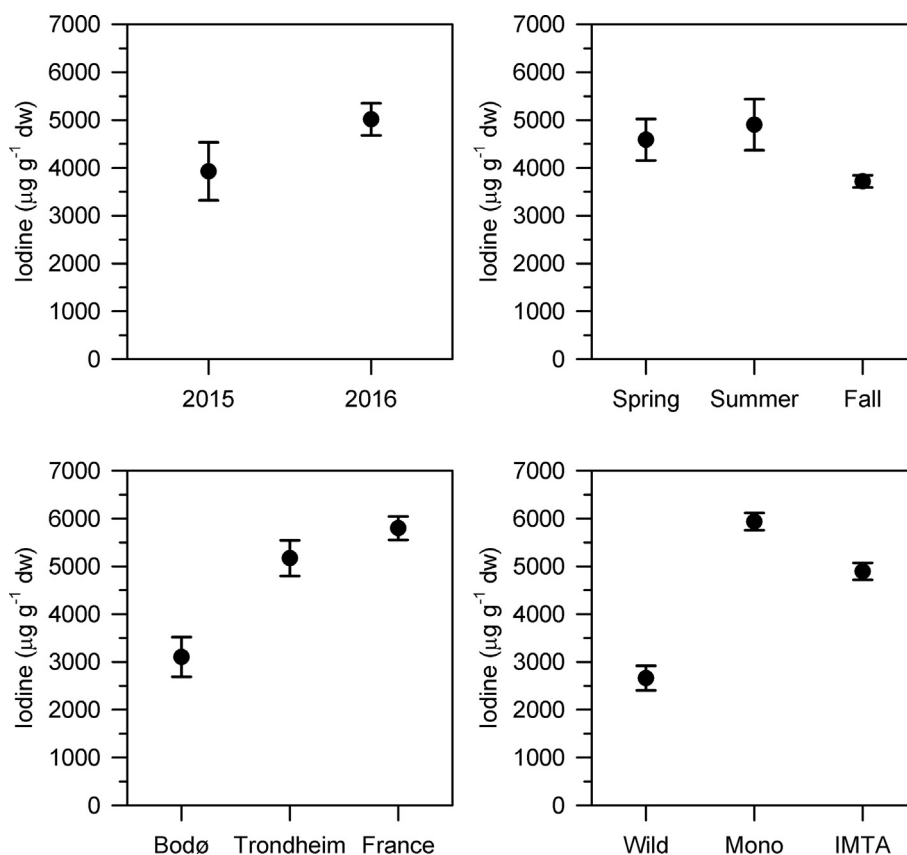

Fig. 2. Variations in the mean iodine content in dried bulk biomass of the brown alga *Saccharina latissima*. Data are means ± s.e.; data are given in Table S2 (Supplementary material). Statistical results are summarized in Table 1.

Table 1

Summary of results of statistical analyses. Mean iodine contents in bulk biomass of three edible macroalgal species (*Saccharina*, *Alaria*, *Palmaria*) were determined during two years at three different seasons from various locations and sources. Differences between sampling years (2015, 2016) and location (for *Palmaria*: Bodø, Trondheim) were assessed by *t* tests; *effects* of 'season' (spring, summer, fall), 'location' (for *Saccharina* and *Alaria*: Bodø, Trondheim, France) and 'source'(f or *Saccharina* and *Alaria*: wild, monoculture, IMTA) were detected by 1-way ANOVAs. The test statistics (*t* or *F*), including degrees of freedom (as subscripts), and *P* values are presented. Where the 1-way ANOVA indicated a significant effect, Tukey *post hoc* tests were applied to find homogeneous sub-groups of means that differed significantly. The data are shown in Figs. 2–4 and in Table S1 (Supplementary materials).

	test statistic	*P* value	*Post hoc*
Saccharina			
Year	$t_{25} = -1.708$	0.100	
Season	$F_{2,24} = 0.457$	0.639	
Location	$F_{2,24} = 8.673$	**0.001**	France = Trondheim > Bodo
Source	$F_{2,24} = 65.864$	**< 0.001**	Mono ≥ IMTA > wild
Alaria			
Year	$t_{20} = -1.066$	0.299	
Season	$F_{2,19} = 1.009$	0.383	
Location	$F_{2,19} = 3.167$	0.065	
Source	$F_{2,19} = 2.731$	0.091	
Palmaria			
Year	$t_9 = -0.856$	0.414	
Season	$F_{2,8} = 0.920$	0.437	
Location	$t_8 = 0.570$	0.584	

with the aid of an Acclaim Mixed-Mode WAX-1 column, which was protected by an Acclaim Mixed-Mode WAX-1 guard column (Dionex Corporation, Sunnyvale, USA). The mobile phase was 50/50 (v/v) methanol/120 mM phosphate buffer (pH 3.00 ± 0.02). I⁻ eluted was detected by a diode array detector at λ = 223 nm, identified via

retention time and the unique absorption characteristics, and quantified by peak area. All analyses were accompanied by positive and negative controls to ensure the validity of results. The method limit of detection (LODHPLC) is ~ 0.2 ng·µL⁻¹; the limit of quantification (LOQHPLC) of the HPLC method is 1 ng·µL⁻¹. Considering a seaweed dry biomass of 200 mg, i.e. the maximum algal biomass that can be reliably analyzed with the HPLC method, the sample LOD$_{seaweed}$ and sample LOQ$_{seaweed}$ are 5 µg g⁻¹ dw and 25 µg g⁻¹ dw, respectively. Here, iodine contents are presented µg g⁻¹ dw to aid comparison with other studies.

2.3. Data treatment and statistical analysis

The average value of triplicate measurements $\overline{x}_{triplicate}$ was considered an independent replicate; the spread of these triplicates represents technical variance. However, parametric tests such as the *t* test and ANOVAs require an estimate for the biological variance to test for *effects* of explanatory variables. Here, the explanatory variables are 'species', 'year', 'season', 'location' and 'source'. The biological variance for one specific explanatory variable was estimated by arraying $\overline{x}_{triplicate}$ across all other explanatory variables; e.g., biological variances for the two levels of 'year' (2015 and 2016) were estimated by considering $\overline{x}_{triplicate}$ values for 'season', 'location' and 'source' at the respective level of 'year'. The treated data are presented as means and standard errors (s.e.) of the independent replicates. Differences in mean iodine concentrations among species were determined by the non-parametric Kruskal-Wallis *H* test followed by multiple comparisons using Mann-Whitney *U* tests; the *P* value was corrected according to the Bonferroni procedure. The non-parametric tests were conducted as the assumptions for parametric tests were violated. The *effects* of 'year' (for all species) and 'location' (for *P. palmata*), on the response variable 'mean iodine content' were determined by using *t* tests; *effects* of 'season',
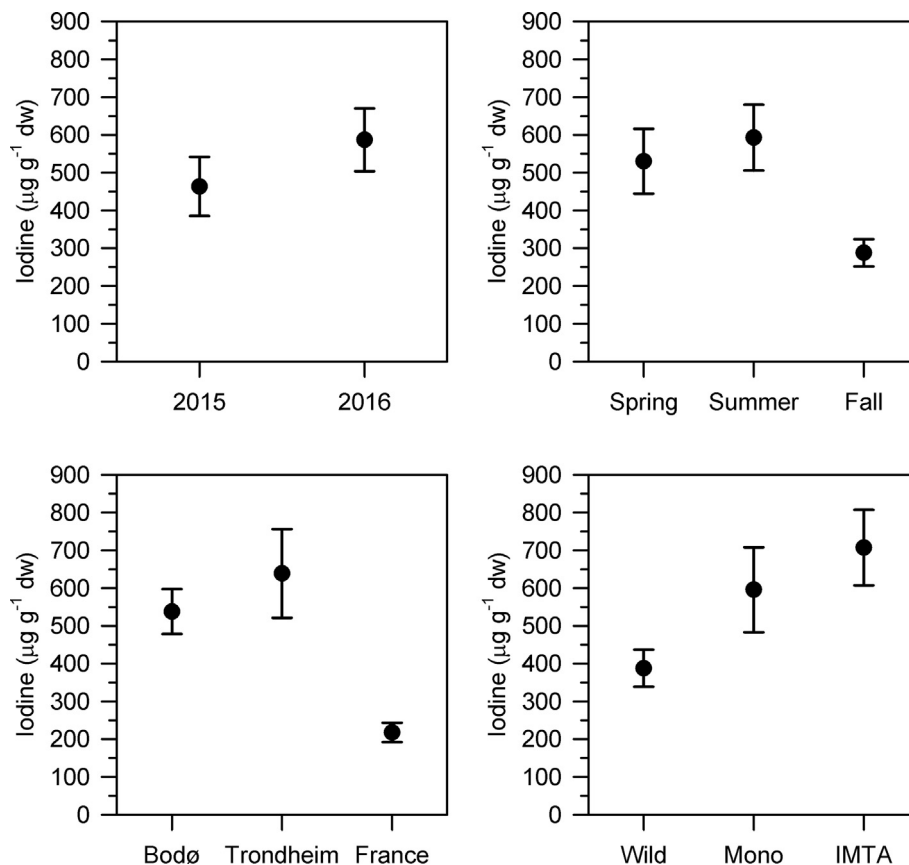
Fig. 3. Variations in the mean iodine content in dried bulk biomass of the brown alga *Alaria esculenta*. Data are means ± s.e.; data are given in Table S2 (Supplementary material). Statistical results are summarized in Table 1.
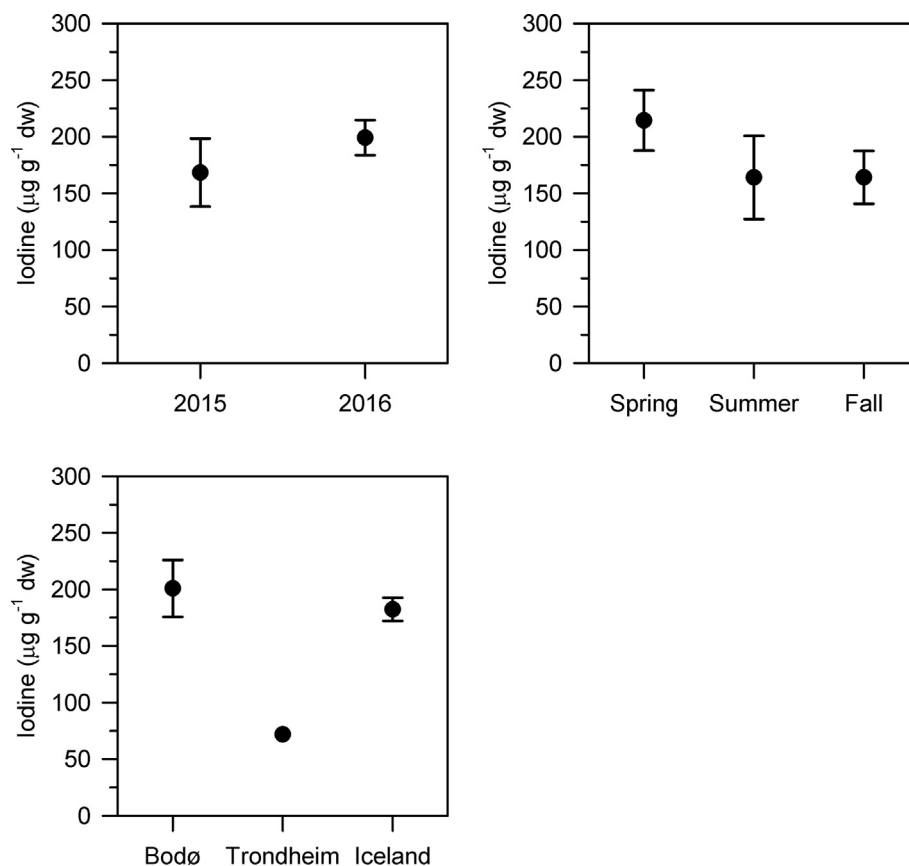
Fig. 4. Variations in the mean iodine content in bulk biomass of the red alga *Palmaria palmata*. Data are means ± s.e.; data are given in Table S2 (Supplementary material). Statistical results are summarized in Table 1.

'location' and 'source' were assessed by applying 1-way ANOVAs. Tukey tests were used to find *a posteriori* homogeneous sub-groups of means that differed significantly at $\alpha \leq 0.05$. In the latter case, most data were normally distributed (Shapiro-Wilk test: $P > 0.05$) and biological variances were homogenous (Levene's test: $P > 0.005$). It should be noted that the sampling strategy was not fully balanced, thus disallowing the application of multi-way ANOVAs. Statistical analyses were performed using IBM® SPSS® Statistics version 24; data were plotted with SigmaPlot® version 13.

3. Results and discussion

3.1. Species-specific iodine concentration

Iodine concentration, regardless of independent variables, was significantly highest in *Saccharina* and lowest in *Palmaria* (Fig. 1, Table S1). Iodine concentration in bulk *Saccharina* biomass (this study: 1556–7208 µg g^{-1} dw) was within the range reported for different tissue parts (= 3579–6130 µg g^{-1} dw), lowest in the older distal portion of the blade and highest in the holdfast, for the same species from Ireland (Nitschke & Stengel, 2015). This study analyzed 27 independent samples of *Saccharina* over a 2-year period compared to the one-time snapshot measurement by Nitschke and Stengel (2015). Our results suggest that the measurement of iodine concentration on bulk seaweed biomass provided thus a very precise average even though individual and intra-thallus variability may be large. Therefore, our measurements appear to serve as a very good proxy to report values for industrial and commercial applications.

Iodine concentration in *Alaria* ranged from 171 to 1070 µg g^{-1} dw. This was higher than the concentration reported (110 µg g^{-1} dw) for the same species from Maine, USA (Teas, Pino, Critchley, & Braverman,

2004), suggesting some large-scale spatial variation between the NE and NW Atlantic samples. The same authors reported iodine concentration in *Palmaria* (72 µg g^{-1} dw) to be within the lower range of those measured in the present study (72 µg g^{-1} dw); however, our results demonstrate that iodine concentrations in this species could be as high as 293 µg g^{-1} dw. These results therefore suggest that not only brown but also red seaweeds can be a rich source of iodine, which is consistent with findings from Ireland (Nitschke & Stengel, 2015) and the Seas of Japan and Okhotsk (Saenko, et al., 1978).

Brown seaweeds of the order Laminariales (kelps) are known to be the strongest accumulators of iodine (Küpper et al., 2008). However, within the order, species-specific differences are also apparent (*Laminaria digitata* > *Laminaria hyperborea* > *Saccharina latissima* > *Alaria esculenta*; Haug & Jensen, 1954; Nitschke & Stengel, 2015; and this study). Conversely, brown seaweeds within the order Fucales have lower iodine concentrations than Laminariales (Nitschke & Stengel, 2015). However, the reported species-specific variations neither appear to be correlated to their habitat or depth distribution, nor their gross and cellular morphology. The species-specificity in iodine content observed in this study may be linked to their volume-to-surface ratio as previously proposed for the differences between juvenile and mature sporophytes of the kelp *L. digitata* (Ar Gall, et al., 2004).

3.2. Variability within species: temporal, spatial, and biomass source

Iodine levels in *Saccharina* bulk biomass did not differ between years or seasons but varied between locations and biomass source (Fig. 2; Table 1). On the other hand, no independent variables caused significant changes in the iodine concentration of *Alaria* (Fig. 3; Table 1) or *Palmaria* (Fig. 4; Table 1).

In *Saccharina*, iodine concentration was lowest in biomass collected

in northern Norway (Bodø) and highest in that from the southern populations (Trondheim and France; Fig. 2, Table S2). This is the first study reporting a large (2 × difference) spatial variability in iodine content from the same species. The lower temperature and long winters in Bodø (Norway) may have contributed to lower iodine bio-accumulation (Ar Gall, et al., 2004). However, our findings were inconsistent among species, and the mean iodine contents in bulk biomass of *Alaria* and *Palmaria* were similar regardless of sampling time and location. *Saccharina* absorbs iodine from seawater with the aid of a haloperoxidase system (Küpper et al., 1998), the activity of which is likely to be influenced by temperature. A temperature-dependent iodide acquisition was previously reported in an invertebrate species but not seaweeds: higher temperature (21 °C) increased iodide influx than that at lower temperature (4 °C) in the larvae of sea urchin, in the absence of food, acquiring iodide directly from the environment (Miller & Heyland, 2013). In contrast to *Saccharina*, processes involved in iodine accumulation by *Alaria* and *Palmaria* are, to date, unknown. Whether the latter two seaweed species also exhibit a temperature-dependent mechanism remains to be investigated. Conversely, a previous study by Lüning and Mortensen (2015) on geographic variability (with confounding seasonal effects) in iodine contents of *Saccharina* did not reveal a spatial trend as observed in this study. They reported higher iodine contents in *Saccharina* harvested from rope culture at sea and in tank cultivation with high turnover of seawater (Lüning & Mortensen, 2015). Low turnover of seawater in tank cultivation was considered to be responsible for the rapid depletion of iodine in seawater, resulting in the lower iodine content measured (Lüning & Mortensen, 2015).

Moreover, it appears that wild biomass that is periodically exposed to air during low tide contains lower iodine concentrations compared to persistently submerged, cultivated biomass regardless of the cultivation system (Monoculture or IMTA). When kelps are submerged (and presumably unstressed), they accumulate iodide from seawater via a vanadium-dependent haloperoxidase system; when environmental factors provoke oxidative stress, iodide is released to detoxify reactive oxygen species (ROS) (Küpper et al., 2008). Previously, exposure to air during low tide was shown to induce the release of molecular iodine from the kelps into the atmosphere (Nitschke, Dixneuf, Schmid, Ruth, & Stengel, 2015), which may explain the observed lower iodine concentrations in wild, compared to cultivated, *Saccharina* and *Alaria*.

3.3. Thallus age

Wild juvenile kelp sporophytes (up to 30 cm in length) had a higher iodine content than wild adult sporophytes (> 1 m) (Fig. 5; Table S1). This trend observed is comparable to results reported for *L. digitata* where juvenile sporophyte (< 15-cm size class) had an iodine concentration up to 12 × higher than adult sporophytes (ca. 1-m size class) (Küpper et al., 1998). Other studies (e.g. Teas, et al. 2004; Ar Gall, et al., 2004) also reported higher iodine concentration in the meristematic region and juveniles compared to non-meristematic thallus sections and adult individuals, respectively. This was most likely related to the transport of iodine towards the meristematic region of the thallus, as reported for *Saccharina* (Amat & Srivastava, 1985). Typically the biological significance of iodine accumulation in seaweeds includes production of iodinated antimicrobial molecules and serves as inorganic antioxidant scavenging a variety of reactive oxygen species (ROS) during oxidative stress (e.g. Küpper et al., 2008; La Barre, Potin, Leblanc, & Delage, 2010).

3.4. Cultivation depth

Cultivation depth (2, 5, 8 m) did not have any significant effect on the iodine (range 4478–4790 $\mu g\,g^{-1}$ dw) concentration of *Saccharina* (Fig. S1; Table S1). This may be related to the fact that seaweeds primarily accumulate iodide present in seawater and the vertical distribution of this iodine species within the euphotic zone down to 150 m
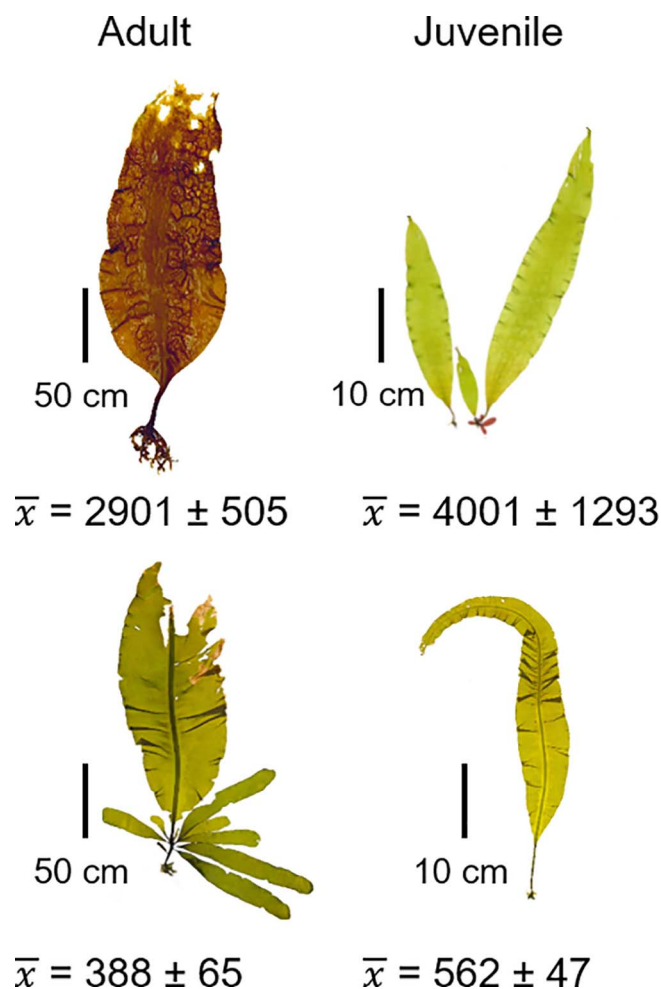

Fig. 5. Age-specific differences in iodine content ($\mu g\,g^{-1}$ dw) in wild harvested kelps (*Saccharina latissima* ($n = 3$), above and *Alaria esculenta* ($n = 2$), below) during 2016 in Bodø Norway. Values are means ± s.e.; data are given in Table S1 (Supplementary material). Statistical differences were not detected due to low number of biological replicates. Images are copyright Michael Y. Roleda.

is relatively stable (Huang et al., 2005). Moreover, high kelp density increases iodide concentration in seawater; this is then available for re-uptake (Gonzales, Tymon, Küpper, Edwards, & Carrano, 2017) and may result in homogenous iodine concentration in biomass cultivated at different depths.

3.5. Implications for biochemical analyses in large-scale commercial harvesting and utilization

Our study suggests that measurement of iodine (and likely other biochemical components) can be reliably conducted in the subsample of bulk biomass derived from large-scale commercial harvesting. The concentrations determined here have provided a precise average (as indicated by low s.e.) that accounts for the large variability often detected at individual and/or thallus part levels. Thus, small subsamples can be excellent representatives of homogenized bulk biomass and may be used as proxies to characterize large quantities of seaweed biomass with regard to their biochemical composition.

4. Conclusion

Our study has demonstrated that iodine concentration in bulk seaweed biomass is largely species-specific (*Saccharina* > *Alaria* > *Palmaria*). In *Saccharina*, iodine concentration were similar across years and seasons, but varied significantly between locations and biomass sources. In *Alaria*

and *Palmaria*, none of the independent variables investigated (i.e. year, season, location and biomass source) caused significant variations in iodine content. When considering the inclusion of seaweed as source of iodine in the diet, it is anticipated that, with regard to iodine levels, seaweed can be consumed conservatively without causing imminent adverse health effects, but excessive and prolonged exposure to high iodine concentrations could bear some health risks. Considering the 150 μg RDI of iodine for adults, as little as 32, 283, or 2149 mg of unprocessed dry biomass of *Saccharina*, *Alaria*, or *Palmaria*, respectively may be consumed daily to reach adequate iodine levels. Currently, the European Food Safety Authority (EFSA) allows 600 μg day^{-1} upper tolerable iodine intake (EFSA NDA Panel, 2014) which permits the consumption of larger quantities of seaweed, among other iodine sources. Despite high levels of iodine present in some seaweeds, ingestion of large amounts will not necessary imply a risk for excessive intake of iodine. Also, post-harvest processing such as drying and boiling in freshwater reduces iodine content in seaweeds within a couple of minutes (Lüning & Mortensen, 2015; Nitschke & Stengel, 2016). In addition, only 49–82% of seaweed iodine appeared to be accessible for absorption by humans after gastrointestinal digestion (Domínguez-González, et al., 2017). Therefore, concerns over iodine toxicity from eating seaweed appears to be unfounded. However, seaweed must be sourced from near-pristine and clean environments, where there is no concern for biological and chemical contamination or other environmental pollutants.

Acknowledgements

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2018.02.024.

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