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Evaluation of nutrient bioextraction by seaweed and shellfish aquaculture in Korea

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Abstract

Although Korea is third in seaweed production and second in shellfish production globally, this is the first study evaluating ecosystem services of seaweed and shellfish aquaculture in Korea. The objective of this study is to evaluate nutrient bioextraction capacities of major seaweed and shellfish species aquacultured in Korea. C (C) removal of three major aquacultured seaweed species, *Neopyropia yezoensis*, *Saccharina japonica*, and *Undaria pinnatifida* were 24,247, 8,423, and 12,758 tons, respectively, in 2016. N (N) removal of these species was 4,088, 732, and 1,244 tons, respectively. The C and N removal of the Pacific oysters (*Crassostrea gigas*) were 14,693 and 1,050 tons, respectively. Manila clams (*Venerupis philippinarum*) removed 2,120 tons of C and 136.5 tons of N. Together, 161,846 tons of CO_2 and 7,251 tons of N were removed by three major seaweed species and two shellfish species. These values are significant amounts, equivalent to 5.7% of CO_2 and 8.6% of N discharged from all wastewater treatment plants in Korea. These results suggest that nutrient bioextraction by aquacultured seaweed and shellfish can be a cost efficient, affordable, and equitable solution for coastal nutrient management programs in Korea and elsewhere.

Sook Kyung Shin is the first co-author.

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KEYWORDS
Crassostrea gigas, *Neopyropia yezoensis*, nutrient bioextraction, *Saccharina japonica*, seaweed aquaculture, shellfish aquaculture, *Undaria pinnatifida*, *Venerupis philippinarum*

1 | INTRODUCTION

Korea is one of the leading countries in aquaculture (FAO, 2020). The growth of aquaculture in production in Korea has increased by nearly 300% (>6% annual growth rate) during the past 30 years. The aquaculture production in 2018 was nearly 2.3 million m.t., while the production in 1989 was only 788,000 m.t. The commercial value of aquaculture in 2018 was over $3.1 billion (FAO, 2020). The Korean aquaculture production is dominated by seaweed, 1.7 million m.t., followed by shellfish, 417,000 m.t., and finfish, 102,000 m.t., in 2018 (FAO, 2020). *Saccharina japonica* and *Undaria pinnatifida*, and "*Pyropia yezoensis*" (currently regarded as *Neopyropia yezoensis*), occupy nearly 97% of entire seaweed production in Korea. Among shellfish species, the Pacific oyster, *Crassostrea gigas* is the most important species in Korea, occupying over 75% of total shellfish production (Ministry of Oceans and Fisheries, 2018) followed by blue mussels (*Mytilus edulis*; 15%) and Manila clams (*Venerupis philippinarum*; 4%). Over 90% of seaweed aquaculture occurs in Jeonnam Province, southwestern Korea, and over 80% of shellfish and 90% of oysters are produced in Gyeongnam Province, southeast of the country (Ministry of Oceans and Fisheries, 2018).

Seaweed and shellfish aquaculture serve ecosystem services through (a) producing primary production and providing structure to support food webs, (b) supplying seafood, and (c) improving the quality of coastal waters. In the present study, we focused only on the third role, improving the environment via removing inorganic and organically bound nutrients from the ecosystem. Seaweed and shellfish aquaculture have been suggested as an efficient way to remediate nutrients from eutrophic waters such as urbanized estuaries (Galimany, Rose, Dixon, & Wikfors, 2013; Kim, Kraemer, & Yarish, 2014, 2015, 2019; US EPA, 2013). These ecosystem services are now referred to as nutrient bioextraction (Kim, Yarish, Hwang, Park, & Kim, 2017; Rose et al., 2012; Rose, Bricker, & Ferreira, 2015; Tedesco, Opertti, & Amadio, 2014).

The use of extractive aquaculture technologies for nutrient harvesting could provide the public with water quality improvement at relatively low cost while providing jobs and the enhancement of natural resources. Nutrient bioextraction capacities of seaweed and shellfish have been evaluated in many countries (Higgins, Stephenson, & Brown, 2011; Kellogg, Cornwell, Owens, & Paynter, 2013; Kim et al., 2014, 2015, 2019; Lindahl et al., 2005; Newell, 2004; Wu, Kim, Huo, Zhang, & He, 2017; Wu, Zhang, Yarish, He, & Kim, 2018). For instance, by cultivating the brown seaweed *Saccharina latissima* (November to May) and the red seaweed *Gracilaria tikvahiae* (June to October) in the Long Island Sound and New York Estuary, approximately 430 kg N ha^{-1} and 2,100 kg C ha^{-1} could be removed (Kim et al., 2014, 2015). Oysters grown in the Chesapeake Bay can also remove up to 378 kg N ha^{-1}, 54 kg P ha^{-1}, and 11,000 kg C ha^{-1} per year (Kellogg et al., 2013). Since seaweed and shellfish are in different trophic levels, requiring different nutrient sources for their growth (inorganic nutrients for seaweeds vs. organically bound nutrients for shellfish), these two groups of organisms may be co-cultured in an area. Co-cultivation of seaweed and shellfish may even enhance the growth and nutrient bioextraction capacity of both species when high concentrations of nutrients are available (e.g., adjacent to a finfish farm; Chopin, Robinson, Troell, Neori, & Fang, 2008; Park, Shin, Do, Yarish, & Kim, 2018; Ridler et al., 2007; Wang et al., 2014). Although seaweed and shellfish aquaculture are well developed in Korea, the ecosystem services provided by these organisms often fall unnoticed by Korean regulatory authorities and the general public. This is probably because seaweed and shellfish have not been accurately evaluated. The objective of this study is to evaluate nutrient bioextraction capacities of major seaweed and shellfish species aquacultured in Korea.

2 | MATERIALS AND METHODS

Eight seaweed species were collected including: three brown algae, *Ecklonia stolonifera*, *S. japonica*, and *U. pinnatifida*; three red algae, *Gracilaria chorda*, *Palmaria* sp., and *N. yezoensis*; and two green algae, *Codium fragile* and *Ulva* sp. from major seaweed farms in Korea. The collection sites include Dangmok, Wando (Jeonnam; *S. japonica* and *U. pinnatifida*), Jangyong-ri, Wando (Jeonnam; all species except for *N. yezoensis*), Yeosu (Jeonnam; *N. yezoensis*), Kijang (Busan; *S. japonica* and *U. pinnatifida*), and Seosan (Chungnam; *U. pinnatifida*) during the winter–spring harvest period in 2016 (Figure 1, Table S1). The collected seaweed samples (n = 10) were transported to the laboratory in a cooler. After the samples were cleaned with distilled water, fresh weight was obtained after blotting the thalli dry with paper towels. The samples then dried in an oven at 60°C to constant weight and dry weight was measured (Kim et al., 2014, 2015). For *Undaria*, blade, sporophyll, and holdfast were separately prepared for the tissue analysis. The dried samples were ground to a uniform powder using a tissue grinder (MM400 Grinder, Retsch, Haan, Germany). The tissue Carbon (C) and Nitrogen (N) contents were determined using a CHN analyzer (CHNS/O 2400 Analyzer, Perkin Elmer, Waltham, MA, USA).

Two shellfish species, Pacific oysters (*C. gigas*) and Manila clams (*V. philippinarum*), were collected from three different shellfish farms. The sample collection sites include Taean and Seosan (Chungnam; both species) and Tongyoung (Gyeongnam; oysters only) from January to April, 2016 (Figure 1, Table S2). After the samples (n = 10) were transported to the laboratory in a cooler, the shells were cleaned using a wire brush to remove fouling. The fresh weight of soft tissue and shells were measured separately and then dried in an oven at 60°C to constant weight. After the dry weight was measured, the samples were ground and tissue C and N contents were determined following the above-mentioned methods.

For the analysis of tissue C and N contents, and C:N ratio, two-way ANOVAs were used. Data were checked for homogeneity of variance and normality prior to analysis of variance. Tukey's HSD analysis (α = .05) was used as a post-hoc test to determine pairwise comparison probabilities between treatment level means. All analyses were conducted using SPSS Statistics 23 (IBM, Armonk, NY, USA).

3 | RESULTS

3.1 | Tissue C and N contents, and C:N ratio in seaweeds

Tissue C (C) and N (N) contents, and C:N ratios were compared for different species collected from Dangmok and Yeosu in March, 2016. Species significantly influenced tissue C, N, and C:N ratio (p < .001 for all; Table S3). Species with high surface area to volume ratio, *Ulva* (32.63%) and *Neopyropia* (34.84%), showed higher tissue C contents than other seaweed species (20.45–28.97%; Figure 2a). Tissue N contents were higher in the red seaweeds (*Gracilaria*, 3.79%; *Palmaria*, 4.31%; and *Neopyropia*, 5.87%) and a green seaweed, *Ulva* (4.23%) than the other species (Figure 2b). C:N ratios were lower in the red seaweeds (5.75–6.66) than those in the greens and browns, but the values of C:N ratios of all species were relatively low, <12 (Figure 2c).

Saccharina blades were collected from three different sites in March and May. While site did not significantly affect tissue C (p > .05), time and the combination of time and site significantly affected tissue C (p = .004 and p = .007, respectively). Time did not affect tissue N (p > .05), but the effect of site and the combination of site and time were significant (p = .042 and p = .004, respectively). In terms of C:N ratio, time and site had a significant effect (p = .001 for both time and site), while the combination effect of time and site was not significant (p > .05; Figure 3; Table S4).

Undaria blades were collected from four different sites in March and two sites in May. Site and time, and the combination of both significantly affected tissue C and C:N ratio. For tissue N, the effect of site and the combination of time and site was significant (p = .002 for both) while time did not affect (p > .05; Figure 4; Table S5).

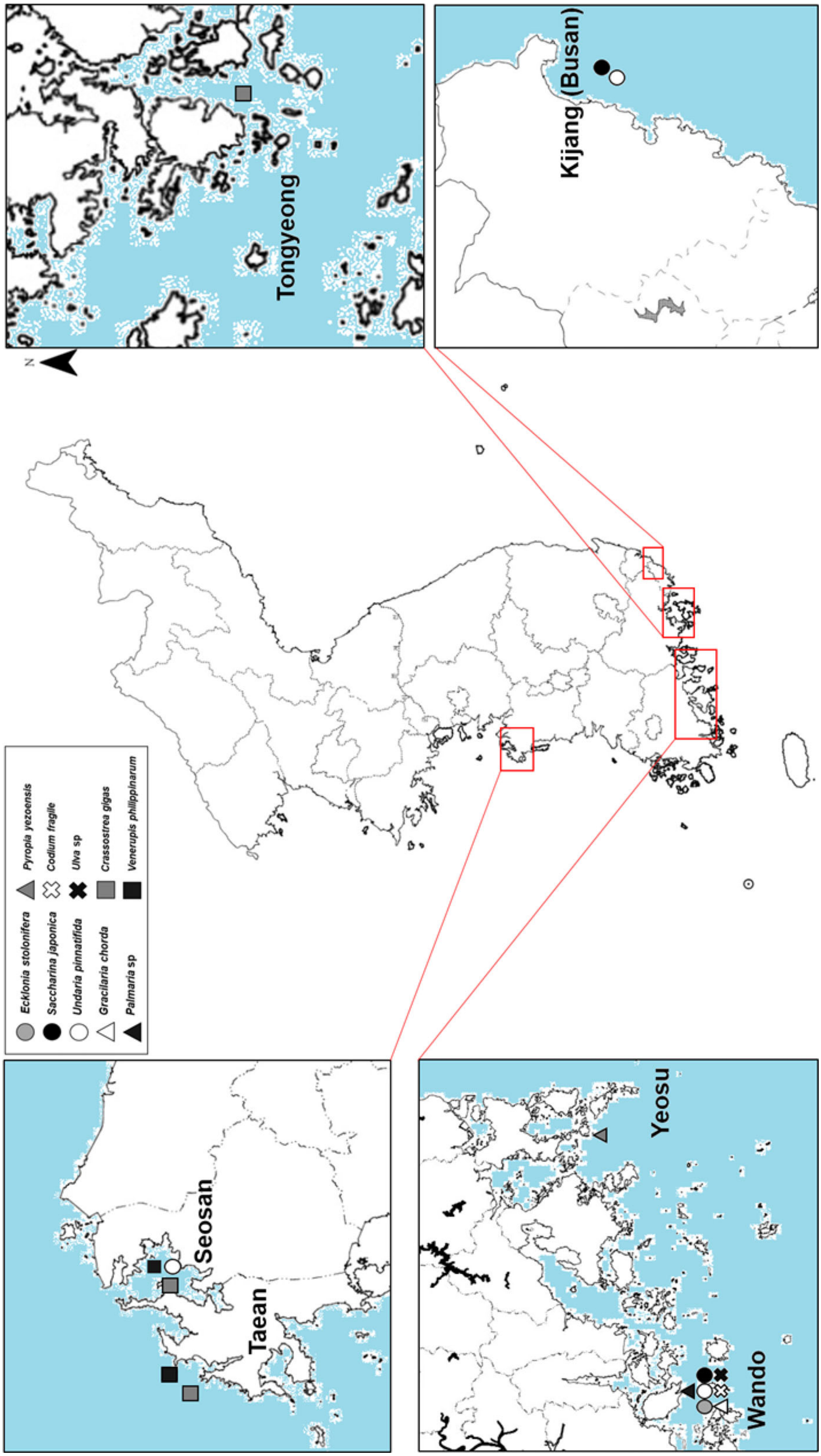

FIGURE 1 The collection sites of seaweed and shellfish

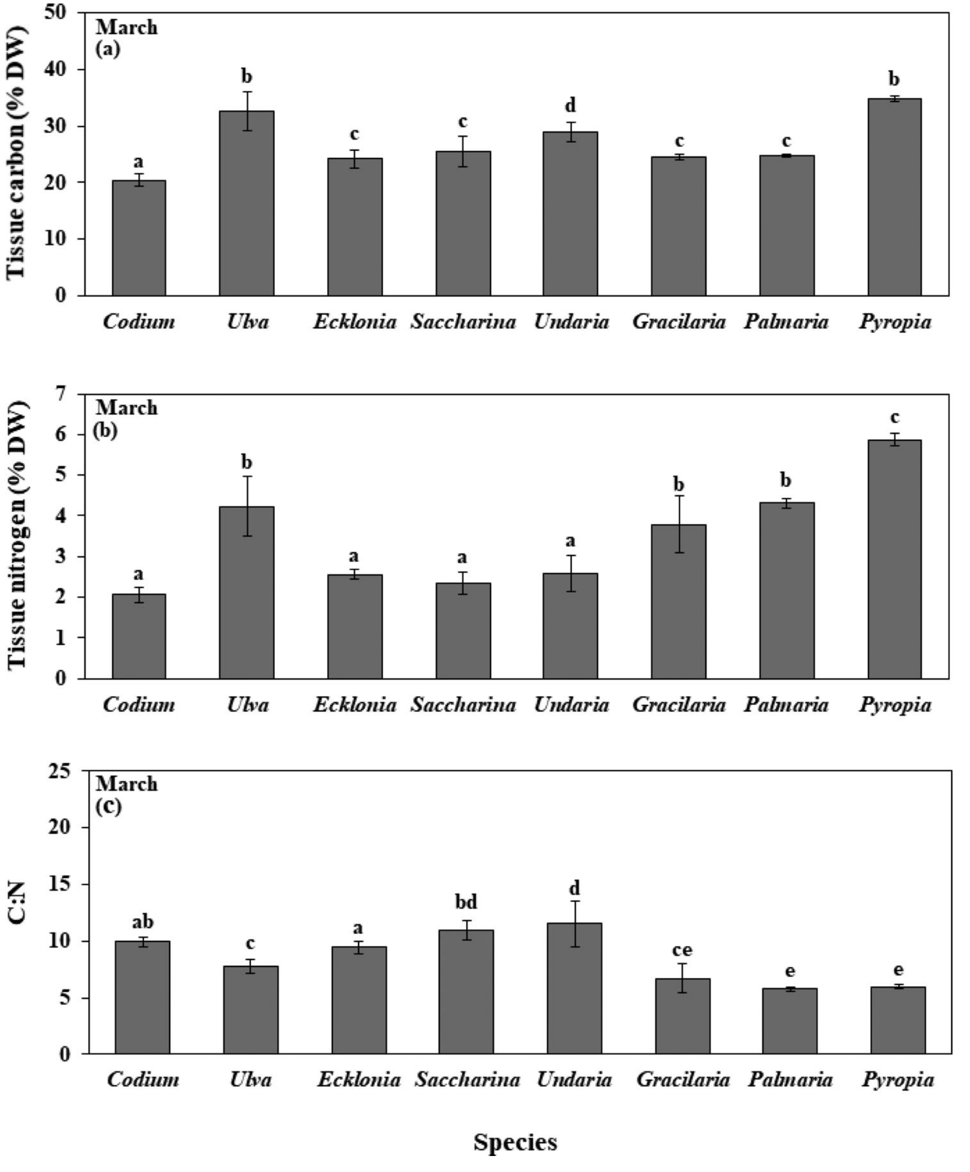

FIGURE 2 Tissue C (a) and N (b) contents, and C:N ratio (c) in different species collected from Dangmok and Yeosu in March, 2016. Each coordinate is the overall mean with standard deviation of 10 samples. The means are not significantly different from the others with sharing the same letter ($p > .05$)

At the Jangyoung-ri site, different parts of *Undaria* thallus (blade, sporophyll and holdfast) were separately collected and analyzed in March and May. For tissue C, the effect of time and thallus part were significant ($p = .006$ and $p < .001$, respectively), while the combination of both was not ($p > .05$). In terms of tissue N, thallus part and the combination of time and part were a significant influence ($p = .022$ and $p < .001$, respectively), while the effect of time was not significant ($p > .05$). Time, thallus part and the combination of both significantly affected C:N ratio ($p = .011$. $p < .001$ and $p = .019$, respectively; Table S6). Tissue N content was highest in the blade and followed by sporophyll and holdfast. C:N ratios, in contrast, were highest in holdfast and followed by sporophyll and blade (Figure 5).

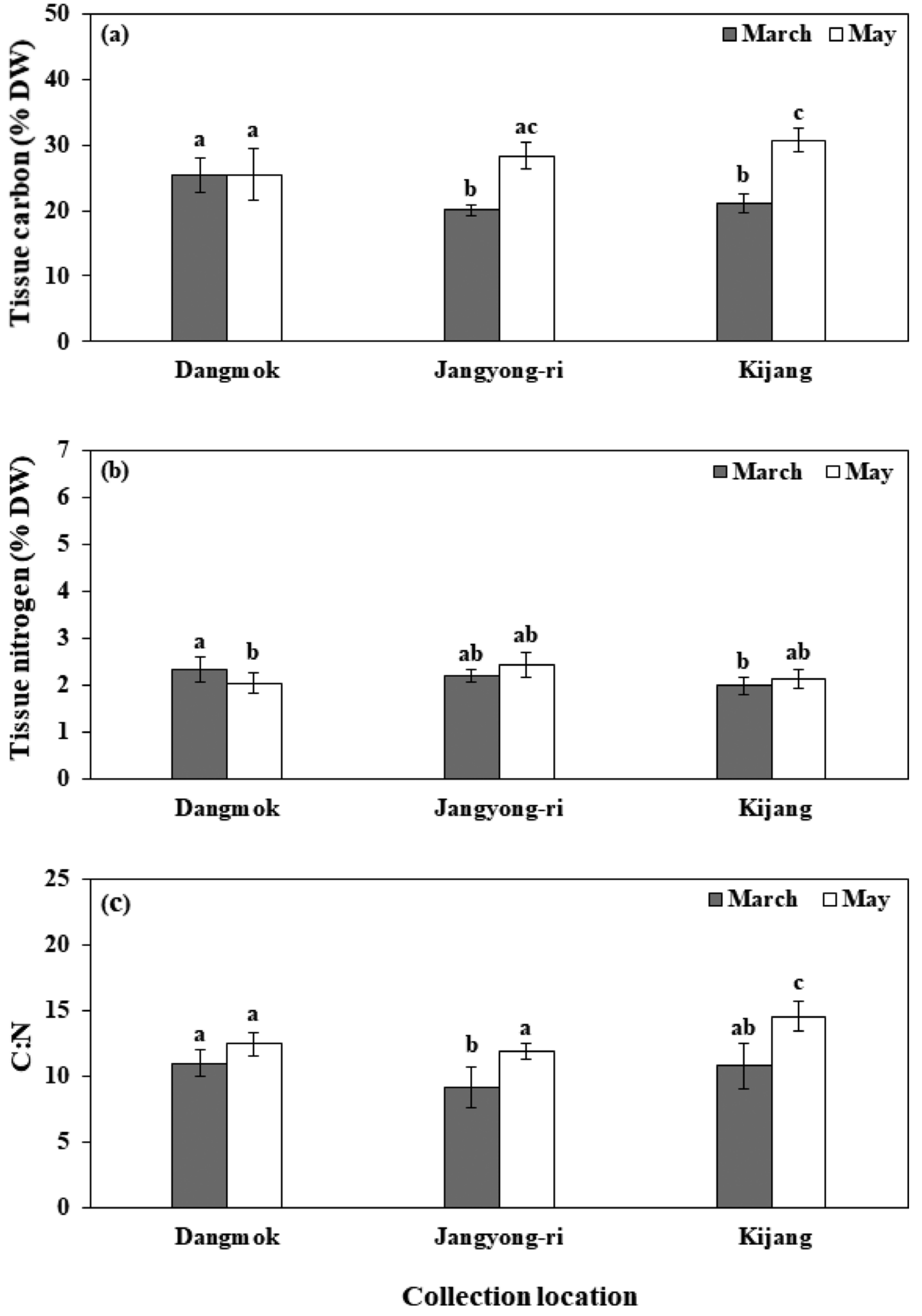

FIGURE 3 Tissue C (a) and N (b) contents, and C:N ratio (c) of *Saccharina japonica* collected from three different sites in March and May, 2016. Each coordinate is the overall mean with standard deviation of 10 samples. The means are not significantly different from the others with sharing the same letter ($p > .05$)

3.2 | Tissue C and N contents, and C:N ratio in shellfish

Tissue C and N contents, and C:N ratio of soft tissue, shell, and together (whole) were analyzed separately. In Pacific oysters (*C. gigas*), tissue C contents of soft tissue were significantly influenced by site ($p < .001$) but not by time and

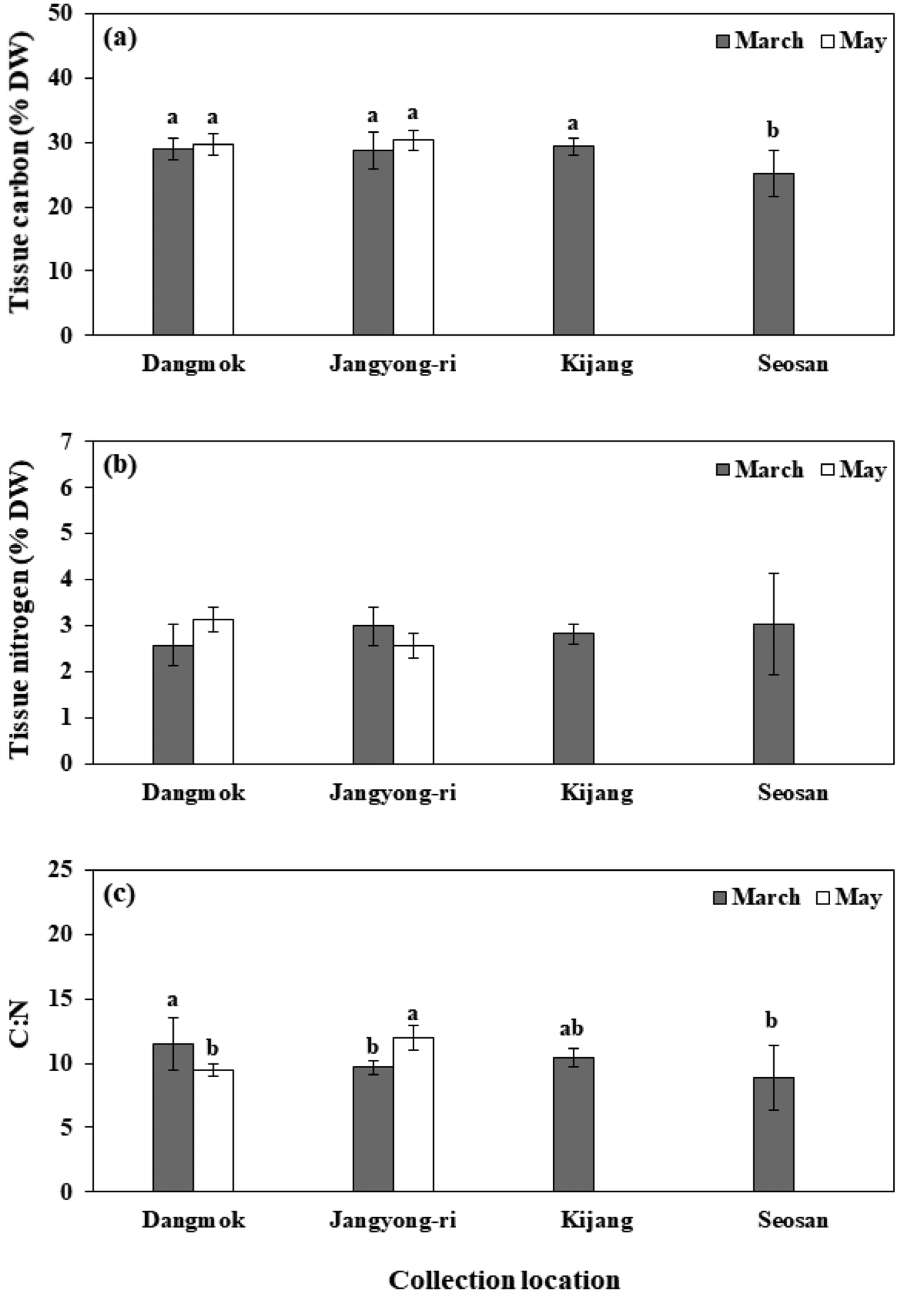

FIGURE 4 Tissue C (a) and N (b) contents, and C:N ratio (c) of *Undaria pinnatifida*, collected from three different sites in March and May, 2016. Each coordinate is the overall mean with standard deviation of 10 samples. The means are not significantly different from the others with sharing the same letter ($p > .05$)

the combination of time and site ($p > .05$). Tissue N contents and C:N ratio of soft tissue were significantly affected by site and the combination of time and site ($p < .001$ for all), while time was not an effect. In the shells, site influenced tissue N and C:N ratio site ($p = .002$ and $p < .001$, respectively), but no significant effects were observed in all other conditions. For the whole oyster, tissue C content was affected by site ($p < .001$) but not by time or the

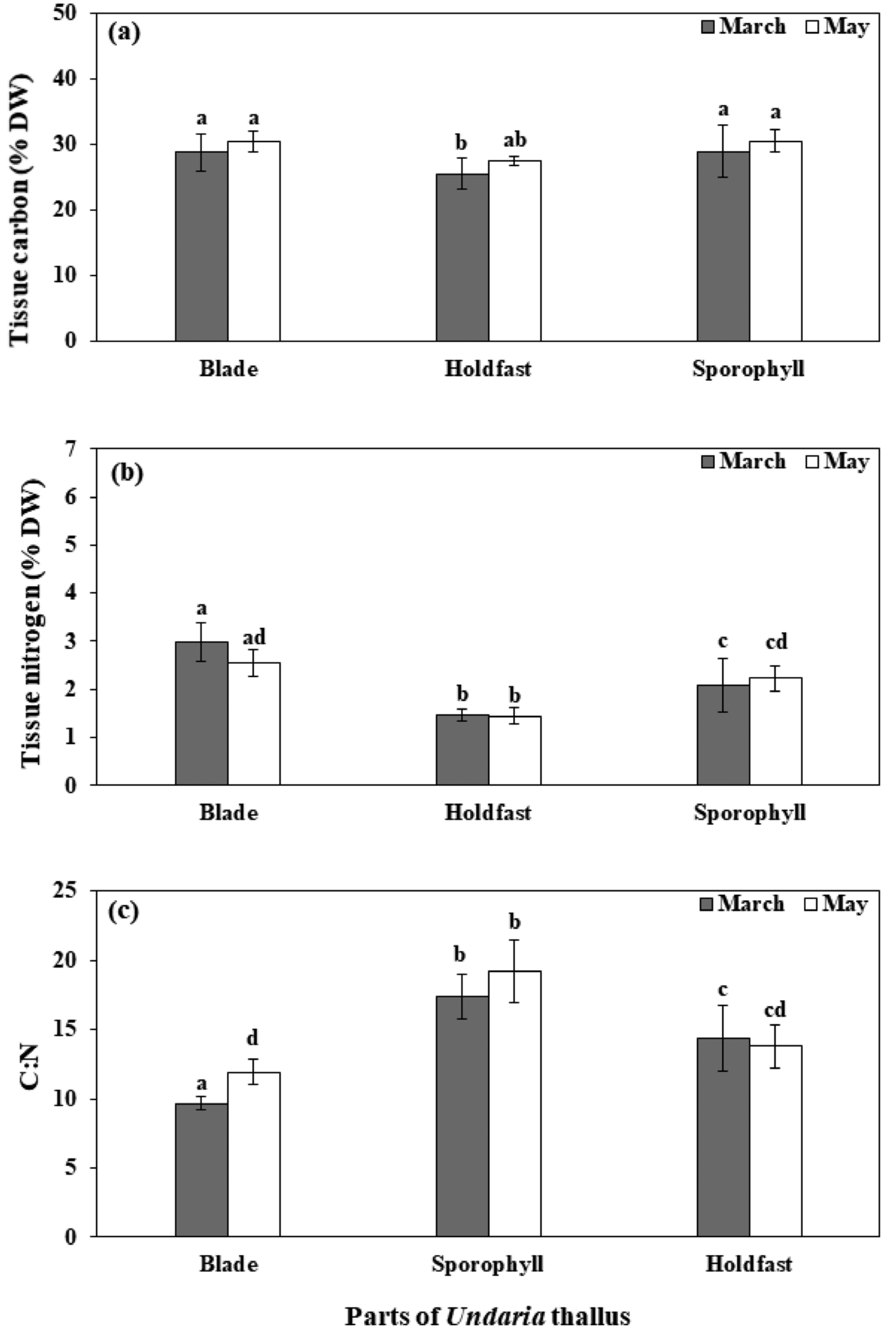

FIGURE 5 Tissue C (a) and N (b) contents, and C:N ratio (c) of different parts of *Undaria pinnatifida* thallus (blade, sporophyll, and holdfast), collected from the Jangyoung-ri sites in March and May, 2016. Each coordinate is the overall mean with standard deviation of 10 samples. The means are not significantly different from the others with sharing the same letter (p > .05)

combination of time and site (p > .05). Time and site significantly affected tissue N and C:N ratios, while the combination of both did not (Figure 6; Table S7). As a whole, tissue C and N contents were higher at Tongyoung (southeast of Korea) than at Seosan and Taean (west). C:N ratios were higher in the west coast farms than that in the southeast

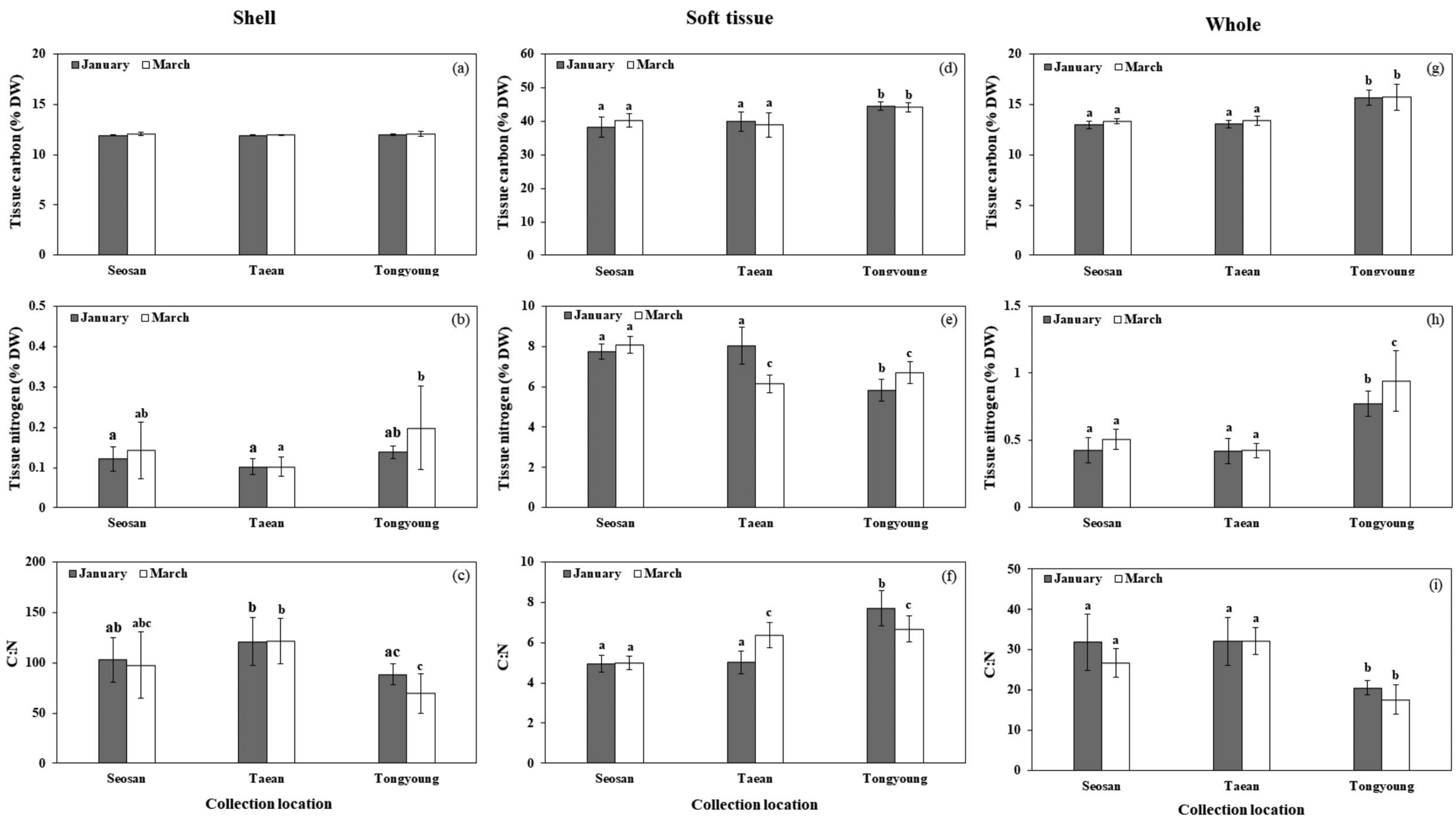

FIGURE 6 Tissue C and N contents, and C:N ratio of different parts of *Crassostrea gigas* (shell, soft tissue, and whole), collected from Seosan, Taean, and Tongyeong in January and March, 2016. Each coordinate is the overall mean with standard deviation of 10 samples. The means are not significantly different from the others with sharing the same letter ($p > .05$) (a,b,c: Shell, d,e,f: Soft tissue, g,h,i: Whole)

ones. Regardless of time and site, tissue C and N contents were much higher in the soft tissue than the shells, but C:N ratio is much higher in shells than soft tissue (Figure 6).

Manila clams (*V. philippinarum*) are cultivated only on the west coast of Korea. This species was collected and analyzed in January and March, 2016, from two different farms, and soft tissue, shell and together (whole) were analyzed separately. Tissue C content and C:N ratio of soft tissues were significantly influenced by time, site and the combination of both. However, tissue N contents were influenced by only time ($p < .001$). Time, site, and the combination of both did not affect tissue C, N, and C:N ratio in the shell ($p > .05$). For the whole Manila clam, tissue C and N contents and C:N ratios were affected by site, time, and the combination of both (Table S8). The Manila clams collected from Seosan showed higher tissue C and N contents and lower C:N ration than those from Taean. Regardless of time and site, tissue C and N contents were much higher in the soft tissues than shells, but C:N ratios are much higher in the shells than soft tissues (Figure 7).

4 | DISCUSSION

Korea is the third country in seaweed production after China and Indonesia and the second country in shellfish production after China (FAO, 2020). Although the nutrient bioextraction by these organisms has been studied in other countries (Alcalde et al., 2018; Aldridge, van de Molen, & Forster, 2012; Bjerregaard et al., 2016; Buschmann et al., 2017; Chopin et al., 1999, 2008; Chopin, Cooper, Reid, Cross, & Moore, 2012; Chopin, Lively, Wiper, & Totten, 2014; Clements & Chopin, 2017; Cottier-Cook et al., 2016; Fang, Zhang, Xiao, Huang, & Liu, 2016; Kelemen, Benson, Pilorgé, Psarras, & Wilcox, 2019; Keller et al., 2018; Krause-Jensen et al., 2018; Milledge & Harvey, 2016; National Academies of Sciences, Engineering,, & Medicine, 2019; Neori et al., 2004; Park et al., 2015, 2018; Park, Yang, Do, & Lee, 2016; Reid et al., 2013; Shi, Zheng, Zhang, Zhu, & Ding, 2013), this is the first study evaluating ecosystem services of seaweed and shellfish aquaculture in Korea. The biomass yield of each species was obtained from the Ministry of Oceans and Fisheries of Korea (2018; Table 1). Combining the biomass yield with the tissue C and N concentration of each species, the nutrient bioextraction capacity of each species was calculated.

C removal of three major aquacultured seaweed species in Korea, *N. yezoensis*, *S. japonica*, and *U. pinnatifida*, was 24,247, 8,423, and 12,758 tons, respectively, in 2016, which are equilibrant to 63,043, 21,918, and 33,171 tons of CO_2, respectively (Table 1). N removal of these species was 4,088, 732, and 1,244 tons, respectively, in 2016. The C and N removal of the Pacific oysters (*C. gigas*) were 14,693 (=38,202 tons of CO_2) and 1,050 tons, respectively, in 2016. During the same time, Manila clams (*V. philippinarum*) removed 2,120 tons of C (= 5,512.0 tons of CO_2) and 136.5 tons of N. Together, 161,846 tons of CO_2 and 7,251 tons of N were removed by three major seaweed species and two shellfish species measured in this study (Table 1). This is the amount equivalent to approximately 8.6% of N and 5.7% of CO_2 discharged from all wastewater treatment plants in Korea.

Recently, the United Nation has launched a seaweed manifesto, entitled "Seaweed Revolution." This manifesto emphasized the importance of seaweed not only for food security but also for climate change mitigation, and support to the marine ecosystems. This report also stated that the role of seaweed to combat climate change may have been largely *underestimated* (Lloyd's Register Foundation, 2020), suggesting an accurate evaluation of nutrient bioextraction by seaweeds (as well as shellfish) must be analyzed. Although many studies evaluated the nutrient bioextraction capacities of seaweed and shellfish aquaculture, only part of them used actual tissue C and N contents, and production values from the study sites (Wu et al., 2017, 2018). For their calculation, some studies used information from literature (Kim et al., 2017; Sondak & Chung, 2015; Xiao et al., 2017) which may not reflect the situation at the study site, and some studies used assumptions (Higgins et al., 2011; Kim et al., 2014, 2015; Lamprianidou, Telfer, & Ross, 2015) that are sometimes unrealistic.

For example, global nutrient bioextraction capacities by seaweed and shellfish aquaculture have been estimated in recent studies (Bouwman et al., 2011; Ferreira, Hawkins, & Bricker, 2011; Kim et al., 2017). These studies mostly used tissue C and N values from literature. The C and N assimilation efficiency varies among species and local

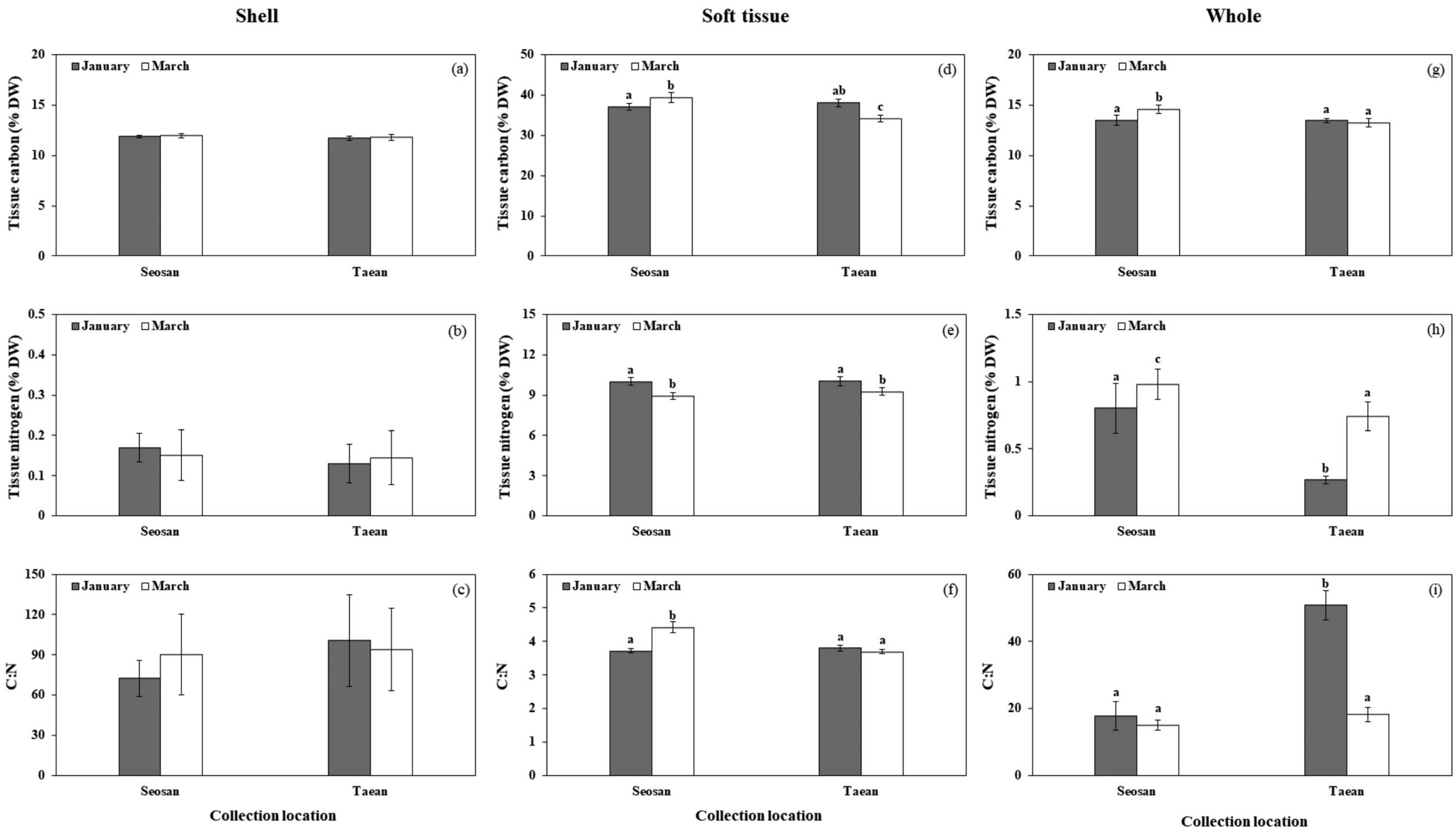

FIGURE 7 Tissue C and N contents, and C:N ratio of different parts of *Venerupis philippinarum* (shell, soft tissue and whole), collected from Seosan, Taean, and Tongyeong in January and March, 2016. Each coordinate is the mean with standard deviation of 10 porophyte samples. The means are not significantly different from the others with sharing the same letter ($p > .05$) (a,b,c: Shell, d,e,f: Soft tissue, g,h,i: Whole)

TABLE 1 Seaweed and shellfish aquaculture production, and C (CO_2) and N by seaweeds and shellfish

		Removal (ton DW year^{-1})	
	Productivity (ton FW year^{-1})	C (CO_2)	N
Crassostrea gigas	282,917	14,693 (38,202)	1,050
Venerupis philippinarum	28,081	2,120 (5,512)	137
Neopyropia yezoensis	409,444	24,247(63,043)	4,088
Saccharina japonica	433,257	8,430 (21,918)	732
Undaria pinnatifida	498,716	12,758 (33,171)	1,244

conditions (Abreu et al., 2009; Kim et al., 2014, 2015; Wu et al., 2017). In other words, the amount of C and N removed from this process will vary in space, in time, and by species. Accurate quantification of C and N removal at a local scale, especially in those countries with high production, therefore, is necessary for seaweed and shellfish farming to be incorporated into nutrient management programs (Duarte, Wu, Xiao, Bruhn, & Krause-Jensen, 2017; Froehlich, Afflerbach, Frazier, & Halpern, 2019; Krause-Jensen et al., 2018). One good example of local study was conducted in one of the largest seaweed farms in the world. Wu et al. (2017) measured the total N removed by *N. yezoensis* aquaculture in the radial sandbanks, Jiangsu Province, China. They estimated that nearly 3,700 tons of N was removed by *Neopyropia* aquaculture in 2012–2013 growing season (Wu et al., 2017). Wu et al. (2018) even estimated nutrient bioextraction capacity of green tide (*Ulva* bloom) in the Yellow Sea, China, which was originated from the *Neopyropia* farms in Jiangsu Province.

Seaweeds are known to be an important CO_2 and N sink. However, a short life span is the biggest limitation for seaweed to be a good organism for C and N sequestration. Seaweed biomass is mostly used for human consumption, animal feed, and hydrocolloids (Park et al., 2018; Pereira & Yarish, 2008; Torres, Kraan, & Domínguez, 2019; White & Wilson, 2015), and therefore, the stored C and N in its tissues may be returned to the environment in a relatively short time period unless the biomass is used in environmentally friendly ways, such as biofuel. The soft tissue of shellfish also has the same limitation. However, the C and N contained within the mollusk shells can persist long term (Aubin, Fontaine, Callier, & Roque d'orbcastel, 2018; Fry, 2012), and these shells are mostly considered as wastes in the marine environment (Chen, Xu, Lv, Huang, & Jiang, 2018; Chung, Jung, & Park, 2020). If properly managed, these shells from shellfish aquaculture can be used as a long-term C and N sink. A proper management strategy may include sinking down the shells into the deep sea burying them in reefs to use the shell as a buffer to neutralize anthropogenic CO_2 uptake, therefore providing substantial negative feedback to coastal acidification (Su et al., 2020). In the present study, the estimated C and N removal by the shells are 9,896 and 223 tons, respectively, for the Pacific oysters, and 1,658, and 22 tons, respectively, for the Manila clams. These values are 69% and 21% of entire C and N removal, respectively, by Pacific oysters and Manila clams harvested in 2016.

Nutrient bioextraction has been considered as a relatively cost-efficient tool for C and N removal (Kim et al., 2019). If seaweed and shellfish are harvested and sold commercially, the cost for C and N removal by the farm can be zero. In some nutrient bioextraction farms, however, the products cannot be sold because of pollution in coastal waters (e.g., bacterial contamination, heavy metals, etc.), and therefore there is insufficient quality of products for human consumption. In this case, payments or credits for nutrient bioextraction will be necessary for farmers to be economically feasible.

Nutrient bioextraction may be included as part of nutrient trading programs for both C and N (Rose et al., 2015). Nutrient trading programs may allow regulated private sector sources to purchase nutrient credits generated from nutrients removed from seaweed or shellfish aquaculture. The State of Virginia in the United States authorized legislation the use of nutrient credits from nutrient bioextraction activities in its nutrient trading program in 2012 (Rose et al., 2015). One may even buy C offsets for his/her home or businesses through nutrient trading programs. Per-capita emission for CO_2 in Korea is 13.6 tons per year, which is one of the top 20 ranked countries in the world (World Bank, 2020). "Buy your C offset" movement may help expand nutrient bioextraction practices more economically feasible in Korea and elsewhere (Alcalde et al., 2018; Bjerregaard et al., 2016; Krause-Jensen et al., 2018). Currently, however, most nutrient trading programs do not include nutrient bioextraction. Additionally, incentives to the nutrient bioextraction farmers, such as capital grant programs, loan programs, and tax incentives, will help enhance nutrient bioextraction technologies (Kim et al., 2015; Rose et al., 2015).

The economic values of C and N removal vary. Recent market values for C and N were in the range from US $6.00 to $60.00/m.t. C [as CO_2] and $5.85 to $125.00/ kg N (America, C. N, 2013; Buschmann et al., 2017; DEEP, C., 2014; Krause-Jensen et al., 2018; Stephenson & Shabman, 2011; Tedesco et al., 2014). The potential economic values of CO_2 and N removal via both seaweed (*Neopyropia*, *Saccharina* and *Undaria*) and shellfish (Pacific oysters and manila clams) aquaculture in Korea, using the above mentioned market values, are $971,000–$9,710,000 for CO_2 and $42,412,000–$906,250,000 for N.

The capacities of C and N removal vary in different species. Considering the above mentioned formula to calculate nutrient bioextraction, tissue C and N contents are important. Seaweed with high SA:V tends to have higher biomass-specific rates of nutrient uptake than species with low SA:V. In contrast, the species with lower SA:V showed a higher nutrient storage capacity (Kim, Kraemer, Neefus, Chung, & Yarish, 2007). In the present study, however, the species with high SA:V (e.g., *Ulva* and *Neopyropia*) had much higher tissue C and N than the species with lower SA:V. *N. yezoensis* and *Ulva* from the radial sandbanks farms, Jiangsu Province, China, also showed very high N assimilation capacities, >7% in *N. yezoensis* and >4% in *Ulva* (Wu et al., 2017). Other studies also showed that *Neopyropia* contains high N in tissue (> 7%), when cultivated in an area with high nutrients, such as near finfish farm (Chopin et al., 1999; Park et al., 2018).

Tissue C and N contents in blade and sporophyll of *U. pinnatifida* were higher than the contents in holdfast, suggesting that blade and sporophyll are the major N storage in this alga, while the holdfast functions for attachment rather than storage. Interestingly tissue C and N contents in blade and sporophyll were similar in the present study. In general, *U. pinnatifida* showed much higher (2–2.5 times) tissue C and N contents in the sporophylls than blades during the reproductive period (Kohtio, 2008). It is probably because the fertile parts of the blade require an accumulation of nutrients for meiospore formation. This meiospore formation may be accomplished by an overflow of excess nutrients from sporophylls (Kumura, Yasui, & Mizuta, 2006). The lower values of tissue C and N in sporophylls in the present study were probably because spent sporophylls were analyzed in the present study.

In shellfish, C and N contents in the soft tissue are much greater than that in shells. C and N contents in Eastern oysters (*Crassostrea virginica*), for example, were on average 11.8–12.4% for C and 0.12–0.32% for N in shells while the values in the soft tissues were much higher, 37.1–46.2% and 7.3–8.6%, respectively (Carmichael, Walton, & Clark, 2012; Grizzle et al., 2017; Higgins et al., 2011; Newell, Fisher, Holyoke, & Cornwell, 2005; Reitsma, Murphy, & Archer, 2014). In the present study, the C and N contents of *C. gigas* and *V. philippinarum* are within the range from the previous studies. C and N concentrations of shellfish vary depending on morphology, environmental conditions and season (Grizzle & Ward, 2016; Kellogg et al., 2014). When breaking the N content down to a percent of the total dry weight (both tissue and shell), N content in oysters from Tongyeong was significantly higher than that from other sites. This result indicates that oysters at Tongyeong obtained more nutrients (food) from nearby finfish farms since this area is one of the core finfish farming areas in Korea (Park et al., 2018).

In conclusion, the findings in this study have shown that nutrient bioextraction capacity by seaweed and shellfish aquaculture can be a cost-effective and equitable solution to mitigate eutrophic coastal waters in Korea and elsewhere. The nutrient bioextraction capacity of three major seaweed species (*N. yezoensis*, *S. japonica* and *U. pinnatifida*) and two shellfish species (*C. gigas* and *V. philippinarum*) was over 160,000 tons for CO_2 and over 7,000 tons for N. These values are very significant, approximately 5.7 and 8.6% of CO_2 and N discharges, respectively, from all wastewater treatment plants in Korea. It is also important to note that the evaluation of C and N removal in developed countries where seaweed and shellfish aquaculture is in the developmental phase is still needed. Further quantification will also be required if seaweed and shellfish can be incorporated to combat global climate changes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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