Cultivated seaweed carbon sequestration capacity

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Abstract. The rising of the earth’s temperature and climate change have attracted the attention of many scientists and environmental experts. One of the main strategies being proposed to minimize the acceleration of the earth’s temperature is to increase the potential of carbon sequestration from the atmosphere by taking advantage of the ability of plants, including algae, to utilize carbon dioxide in photosynthetic processes. This study aimed to estimate the carbon sequestration capacity and total carbon sequestration of macroalgae (seaweeds) commonly used in mariculture or in brackish-water pond (tambak) aquaculture. The study was conducted in August 2018 in South Sulawesi Province, Indonesia Carbon sequestration was estimated using the oxygen exchange method. Three maricultured seaweeds (Kappaphycus alvarezii green and brown strains and Eucheuma spinosum) and two pond-cultured seaweeds (Gracilaria verrucosa and Caulerpa racemosa) were studied. Thallus sections weighing 2.46-4.91 g were inserted into clear bottles (270 mL) filled with seawater and incubated for 3 hours (09.00-12.00), with 5 replicates for each seaweed. The bottles were attached to the seaweed culture lines (maricultured seaweeds) or placed in the ponds (pond-cultured seaweeds). Bottles filled with ambient water (containing phytoplankton) were used as controls. After 3 hours, titration was used to measure the oxygen exchange in each bottle, and the results converted into carbon sequestration. Seaweed productivity ranged from 0.660-11.997 mgCO₂/gbk/hour with the lowest sequestration by K. alvarezii green strain and the highest by E. spinosum. Carbon sequestration was estimated at 57.64 tons CO₂/ha/year for mariculture and 12.38 tons CO₂/ha/year for pond culture. The total annual carbon sequestration from seaweed cultivation in South Sulawesi was estimated at 2,656,625 tons CO₂/year from mariculture and 621,377 tons CO₂/year from pond culture.

1. Introduction
One of the global phenomena related to the environment which has recently been widely discussed by environmental experts is global warming. The main cause of global warming is an increase in the concentration of so-called greenhouse gases (mainly carbon dioxide) in the atmosphere, trapping more heat and warming the earth [1]. The impacts of the resulting global climate change will affect many sectors, both directly and indirectly.

There are two main strategies that humans can adopt to minimize the accelerating rise in global temperature. Firstly, reducing carbon emissions from anthropogenic activities and reducing the use of carbon sources that can increase the concentration of carbon dioxide in the atmosphere, such as fossil fuel energy use, forest fires, etc. Secondly, increasing carbon sequestration from the atmosphere through promoting the ability of vegetation or plants to utilize and sequester carbon dioxide through the process of photosynthesis.
Related to the potential utilization of vegetation as carbon sinks, especially in coastal areas, various activities have been carried out, including studies [2–4] as well as direct mitigation actions such as conservation and rehabilitation of mangroves and seagrasses [5,6]. However, to date the mitigation efforts that have been carried out generally tend to be ecosystem based. It cannot be denied that, besides natural vegetation in coastal areas, seaweed cultivation has developed in several regions of Indonesia. Cultivated seaweeds have the potential to absorb carbon through photosynthesis [7–10].

South Sulawesi Province is the largest seaweed producer in Indonesia. In 2016, South Sulawesi Province's produced 3,409,048.2 tons of seaweed from mariculture and brackish-water pond culture, amounting to around 30% of national seaweed production. The cultivated seaweed production of 2,357,244.7 tons was produced from a cultivation area of 46,354.6 ha [11]. Besides the economic implications, mass production of seaweed is also considered to have significant potential in terms of carbon sequestration. According to [12], the binding of carbon by seaweeds (photoautotrophic macroalgae) has the potential to reduce the release of CO\(_2\) into the atmosphere and can help reduce the rate of global warming. Seaweeds are a group of aquatic plants considered to have a high capacity for carbon sequestration compared to terrestrial plants because of their high productivity [13].

The potential for carbon sequestration by cultivated seaweed needs to be studied in detail to obtain important information. To date, efforts to negotiate the trade in blue carbon are often constrained by a lack of data about the potential for carbon sequestration offered by coastal resources. Such data would be very useful to Indonesian delegations negotiating blue carbon trade deals in international forums. Moreover, such information is also required by related stakeholders for coastal resource management.

The aim of this study was to estimate the carbon sequestration of several species or varieties of seaweed cultivated in South Sulawesi, as well as total carbon uptake by seaweed farming activities at sea and in ponds. The results were expected to provide important data to support the establishment of climate change mitigation strategies for stakeholders which could make use of one potential coastal resource, cultivated macroalgae.

2. Materials and Methods
Data collection took place in seaweed cultivation ponds in Takalar District and seaweed mariculture areas in Takalar and Pangkep Districts in August 2018. The selection of these two locations in South Sulawesi, Indonesia, was based on the consideration that these areas both produce large volumes of farmed seaweeds [11]. Observations on carbon absorption capacity and respiration by the seaweeds were conducted in both mariculture and pond cultivation areas. Carbon sequestration and respiration capacity were estimated based on the oxygen exchange method [14,15], using 270 ml clear bottles and 370 ml dark bottles (Figure 1).

![Figure 1. Oxygen exchange method used to measure carbon seaweed uptake: a. seaweed thallus in the clear bottle; b. position of the incubating bottles during incubation in the field (mariculture)](image)
Three types (species or strains) of seaweed (green and brown strains of *Kappaphycus alvarezi* and *Eucheuma spinosum*) were collected from mariculture farms and two species (*Gracilaria verrucosa* and *Caulerpa racemosa*) were collected from ponds used for seaweed culture. Thallus cuttings were collected as samples from each of the cultivated seaweed types (species or variety), with 10 replicates for each maricultured seaweed type and five replicates for the pond-cultured seaweed types. Subsamples of each sample weighing approximately 2.46-4.91 g were inserted into clear bottles filled with ambient seawater (5 replicates) and incubated for 3 hours (09.00-12.00). For maricultured seaweeds, carbon sequestration capacity was measured at a depth of 50 cm, the seaweed planting depth generally used by local farmers. For seaweeds cultivated in brackish-water ponds, the measurements were made by laying the bottles on the bottom of the pond, as is also the case for the seaweeds in cultivation. In addition, ambient seawater (which naturally contains phytoplankton) was also incubated and used as a control and to provide data for the correction factor (3 replicates).

The oxygen exchange method uses changes in dissolved oxygen concentration to detect the ability of seagrasses to release oxygen as a by-product of carbon absorption during photosynthesis. The assumption on which this method is based is that the process of photosynthesis and respiration occur in clear bottles, but not in dark bottles. Oxygen exchange occurring in the clear bottles was used to calculate seaweed productivity using a special formula. Oxygen concentration was measured by titration. Prior to incubation, the initial dissolved oxygen content of the water was measured. After 3 hours, oxygen exchange in the bottles was measured.

The bottles were filled carefully underwater to avoid the occurrence of air bubbles that could affect the measured oxygen concentration. Before closing the lid, 50 grams of seaweed was placed in each seawater-filled bottle. Prior to incubation, seawater oxygen concentration was measured using the Winkler titration method [16] with 5 replicates. The seaweed samples in both clear and dark bottles were then incubated for 3 hours (09.00 to 12.00) [17]. At the end of the incubation, the measurement of dissolved oxygen content was carried out again.

The amount of carbon in the form of CO$_2$ absorbed by seaweed was estimated by conversion of the primary productivity measured. In fact, in addition to carbon in the form of CO$_2$, some carbon in the form of bicarbonate is also absorbed by seaweeds, with the relative proportions depending on the acidity of the water at the time photosynthesis takes place. Conversion of the primary productivity value into an estimation of absorbed CO$_2$ was carried out based on [18], where for every gram of carbon produced, 3.67 g of CO$_2$ is used.

The specific growth rate (SGR) of seaweed cultivated in the sea was measured in both study locations by weighing the initial weight (seedling weight) and the final weight (harvest weight) of 20-28 seaweed clumps. These observations were carried out on seaweed cultivated by farmers. The formula used to analyse specific growth rates was based on [19]:

$$SGR = \{(Wt/W0)^{1/t} - 1\} \times 100\%$$

where: SGR = specific growth rate (%/day), Wt = final weight (g), W0 = average initial weight (g), t = length of cultivation (days).

The SGR value used to estimate carbon sequestration for maricultured species was the mean of 45 values: 4 values obtained from primary data and 41 values based on secondary data from several researchers. Spatial data were aggregated for all species, because the data on the extent of seaweed cultivation areas obtained from the Government of South Sulawesi Province do not separate the different types of seaweed. The value of SGR for seaweeds cultivated in ponds was the mean of all values obtained from secondary data on the growth of *G. verrucosa* and *C. racemosa*.

The estimation of total carbon uptake by seaweed in each study location was based on two parameters: (1) the capacity of seaweed to absorb carbon per unit area, and (2) the seaweed cultivation area data obtained from the relevant agencies in South Sulawesi.
3. Results and Discussion

3.1. Carbon sequestration of seaweed species
Carbon sequestration of seaweeds incubated in clear bottles varied between species and strains. Similar patterns were found for carbon sequestration rates measured in mgCO$_2$/g wet weight/hour (subsequently abbreviated to mgCO$_2$.gww$^{-1}$.h$^{-1}$) (Figure 2a) and in mgCO$_2$/g dry weight/hour (subsequently abbreviated to mgCO$_2$.dww$^{-1}$.h$^{-1}$) (Figure 2b).

**Figure 2.** Absorption of carbon seaweed species cultivated in Takalar and Pangkep: (a) carbon absorption based on wet weight, and (b) carbon absorption based on dry weight.

The notes in parenthesis indicate the strain (Green or Brown) for K. alvarezii, while the letters indicate the cultivation site: T (Takalar) or P (Pangkep).

_Eucheuma spinosum_ cultivated at the Takalar site had the highest carbon absorption rate of 1.130 mgCO$_2$/g wet weight/hour (subsequently abbreviated to mgCO$_2$.gww$^{-1}$.h$^{-1}$) (Figure 2a). The green strain of _Kappaphycus alvarezii_ cultivated at the Pangkep site had the lowest carbon absorption rate of 0.049 mgCO$_2$.gww$^{-1}$.h$^{-1}$. Seaweed of the same strain absorbed five times more carbon when cultivated in Takalar than when grown in Pangkep. One possible reason is that turbidity was quite high at the Pangkep site, while the seawater was clear in Takalar. Therefore the photosynthetic process was likely not optimal in Pangkep.

Of the two different strains of _K. alvarezii_ cultivated at the Takalar site, the brown strain had a higher net productivity compared to the green strain. The two species of seaweed cultivated in the pond area in Takalar also showed variations in carbon sequestration. _Caulerpa lentillifera_ known by the local community as _lawi-lawi_ had a lower carbon absorption rate (0.286 mgCO$_2$.gww$^{-1}$.h$^{-1}$) than _Gracilaria verrucosa_ (0.927 mgCO$_2$.gww$^{-1}$.h$^{-1}$) (Figure 2a).
Similar to the carbon absorption rates based on wet weight, the highest carbon absorption rate based on dry weight was highest for *Eucheuma spinosum* cultivated in Takalar (11.997 mgCO$_2$.gdw$^{-1}$.h$^{-1}$) and lowest for the green strain of *Kappaphycus alvarezii* cultivated in Pangkep (0.660 mgCO$_2$.gdw$^{-1}$.h$^{-1}$) (Figure 2b). The ratio between dry weight and wet weight was similar for all seaweed types, with a ratio of dry weight to wet weight ranging from 0.070 to 0.102 for maricultured seaweeds and 0.039-0.157 for seaweed cultivated in ponds.

3.2. **Seaweed Specific Growth Rates**

The specific growth rate (SGR) of maricultured seaweed did not differ significantly between cultivation areas or between species. SGR ranged from 2.93 to 3.58%/day (Figure 3). Data on SGR obtained from several studies (secondary data) gave mean specific growth rates for maricultured seaweed of 4.1%/day (n = 36) for *K. alvarezii* and 2.8 %/day (n = 5) for *E. spinosum*. The SGR for *K. alvarezii* was higher than for *E. spinosum*. However, since the available data on maricultured seaweed production are not separated by species, specific growth rate was estimated as the mean of all primary and secondary data (Figure 4). This mean value was then used to estimate seaweed biomass produced over a given cultivation time.

![Figure 3. Specific growth rates of maricultured seaweeds at the two study sites (Takalar and Pangkep)](image3)

![Figure 4. Mean specific growth rate of maricultured seaweeds obtained from a combination of primary and secondary data (45 data points)](image4)

The average SGR of *G. verrucosa* was higher than that of *C. racemosa*, where each species had SGR value as much as 3.5% per day (n = 27) and 0.24% per day (n = 13). Similar to seaweed that was cultivated in marine waters, both seaweed cultivated in these ponds have production data that were not separated, therefore the average SGR value of both species cultivated from ponds was used. The SGR value obtained was 2.3% per day (Figure 5).
3.3. Seaweed Cultivation Area and Production

The total seaweed cultivation area in the coastal waters of South Sulawesi Province was reported as 46,093.5 ha in 2016 [11]. The Takalar study site had the largest cultivation area, with 13,385.7 ha or 29.04% of the total South Sulawesi seaweed cultivation area. No other district had more than 10% of the South Sulawesi seaweed cultivation area. Sinjai District had the smallest extent, 375 ha or 0.81% of the total seaweed cultivation area in South Sulawesi. However, there were no data on the extent of seaweed pond cultivation areas in Selayar District, Maros District and Pare-Pare City (Table 1).

| District       | Area (ha) | Seaweed Production (ton) |
|----------------|-----------|--------------------------|
| Selayar        | NA        | 170.2                    |
| Bulukumba      | 3,225.0   | 158,440.0                |
| Bantaeng       | 3,521.0   | 82,628.0                 |
| Jeneponto      | 3,212.0   | 149,885.1                |
| Takalar        | 13,385.7  | 923,832.0                |
| Sinjai         | 375.0     | 12,220.0                 |
| Maros          | 0.8       | NA                       |
| Pangkep        | 3,254.0   | 202,552.0                |
| Barru          | 250.0     | 891.6                    |
| Bone           | 2,045.1   | 128,204.1                |
| Wajo           | 3,235.0   | 237,900.0                |
| Pinrang        | 3,020.0   | 9,027.4                  |
| Luwu           | 4,543.0   | 244,945.5                |
| Luwu Utara     | 828.9     | 33,930.8                 |
| Luwu Timur     | 4,420.0   | 145,099.0                |
| Pare-Pare      | -         | -                        |
| Palopo         | 778.0     | 25,519.0                 |
| **Total**      | 46,093.5  | 2,357,244.7              |

Data source [11]

Seaweed production in South Sulawesi is divided into two categories based on the cultivation medium, i.e. mariculture and pond aquaculture. The species cultivated in the sea are *Kappaphycus alvarezii* (also known by the no longer valid name *Eucheuma cottonii*) and *Eucheuma spinosum*. While seaweeds cultivated in ponds are *Gracilaria verrucosa* and *Caulerpa lentillifera*. However, *C. lentillifera* cultivation is still very limited and production data were not yet available at the time of this study. Data obtained from the Government of South Sulawesi Province (2018) show that in 2016 there...
were 15 districts with figures for the production of seaweed cultivated in the sea, while no data were recorded for two other coastal districts, i.e. Maros and Pare-Pare (Table 1). While Takalar District was the largest contributor (39.19%) to the total production of South Sulawesi, other districts making a significant contribution included Luwu District (10.39%) and Wajo District (10.09%) (Table 1).

The area of ponds used for seaweed cultivation in South Sulawesi was reported as 50,201 ha. Total production of *Gracilaria verrucosa* seaweed cultivated in ponds in 2016 was 1,051,803.5 tons. This production volume is less than half that of seaweed cultivated in marine waters. Luwu District accounts for the highest proportion of pond cultivated seaweed production, with 295,637.5 tons or 28.11% of the total seaweed production from ponds in South Sulawesi. Takalar District, the largest contributor to maricultured seaweed production, only accounted for 10.50% of total pond cultivated seaweed production in South Sulawesi, while Takalar contributed 110,473 tons.

### 3.4. Total Seaweed Carbon Sequestration

The total carbon sequestration of seaweed in the cultivation areas was obtained from biomass data and the rate of carbon absorption by seaweeds. Biomass value was obtained using several assumptions such as length of the culture cycle and number of culture cycles per year. These assumptions were based on the results of measurements in the field and the results of interviews with seaweed cultivation communities in Takalar and Pangkep Regencies. Using these assumptions, it was estimated that maricultured seaweeds were able to sequester 8.23 tons CO$_2$.ha$^{-1}$.cycle$^{-1}$ or 57.64 tons CO$_2$.ha$^{-1}$.yr$^{-1}$. While the ability of seaweed in the pond cultivation areas to sequester carbon dioxide was lower (1.24 tons CO$_2$.ha$^{-1}$.cycle$^{-1}$ or 12.38 tons CO$_2$.ha$^{-1}$.yr$^{-1}$) (Figure 6).

Based on the estimated capacity of one hectare of cultivated seaweed to sequester carbon (during each cultivation cycle and over a one year period), the total carbon dioxide that could be sequestered by the current level of seaweed cultivation in marine waters of South Sulawesi was estimated as 2,656,625 tons of CO$_2$.yr$^{-1}$. The highest carbon sequestration contribution was from Takalar District, with an estimated 771,492.4 tons.yr$^{-1}$ (Figure 7).

The reported area of ponds currently used for seaweed cultivation in South Sulawesi was 50,201 ha., and the estimated carbon sequestration capacity of one hectare of pond cultivated seaweeds was 12.38 tons CO$_2$.yr$^{-1}$. Therefore, the estimate for the total carbon dioxide uptake by pond-cultivated seaweeds in South Sulawesi was 621,377.2 tons.yr$^{-1}$. 

![Figure 6. Estimated carbon sequestrated per hectare (per cultivation cycle and per year) by seaweeds cultivated in the sea (coastal waters) and in brackish-water ponds in the study areas](image-url)
4. Conclusions

The highest carbon absorption rate found in this study was for *Eucheuma spinosum* maricultured in Takalar District (11.997 mgCO$_2$.gdw$^{-1}$.h$^{-1}$) while carbon absorption rate was lowest in the green strain of *Kappaphycus alvarezi* cultivated in Pangkep District (0.660 mgCO$_2$.gdw$^{-1}$.h$^{-1}$). On average, maricultured seaweeds could sequester 8.23 tons CO$_2$.ha$^{-1}$ per cycle or 57.64 tons CO$_2$.ha$^{-1}$.yr$^{-1}$, while in pond aquaculture areas the estimate was lower, at 1.24 tons CO$_2$.ha$^{-1}$.cycle$^{-1}$ or 12.38 tons CO$_2$.ha$^{-1}$.yr$^{-1}$. Based on a seaweed mariculture area of 46,093.5 ha, the total carbon sequestration in South Sulawesi was estimated as 2,656,625 tons per year. Whereas, with a pond area of 50,201 ha, seaweeds cultivated in ponds could sequester 621,377.2 tons of carbon dioxide per year.

This research was conducted in August 2018, a season when seaweed growth rates are generally below optimal. Thus it is likely that annual carbon uptake by seaweed, both cultivated in marine waters and in ponds, could have been underestimated. Similar research conducted in peak seaweed growing periods (around November to March) is recommended to provide a more representative data set. Such research would complement the current research, improving the estimates of annual carbon sequestration by seaweeds.

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