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Unveiling the potential for artificial upwelling in algae derived carbon sink and nutrient mitigation

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Abstract: Mariculture algae may present a crucial part of ocean-based solutions for climate change, with the ability to sequester carbon and remove nutrients. However, the expansion of mariculture algae faces multiple challenges. Here, we measure the changes in algae derived carbon sinks and nitrogen (N) and phosphorus (P) removal between 2010 and 2020 in Shandong Province, China. We further identify the key driving factors, namely area, algal species proportion, and yield, that influence the changes. The results show that algae derived carbon sinks and nutrient removal growth rates in Shandong Province have slowed significantly since 2014, mainly due to area limitations, laver-oriented species change, and unstable yields. Artificial upwelling (AU) has the potential to enhance the yield and subsequently offset the loss of carbon sinks and nutrient removal caused by negative driving factors. Scenario analysis indicates that a complete deployment of AU by 2030 will offset up to a 44.52% decrease in the mariculture algae area, or a 72.57% increase in the laver share of the algal species combination compared to 2020. Similar conclusions are reached regarding the role of AU in N and P removal. This study also identifies ancillary challenges such as low energy efficiency and high costs faced by applying AU.

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22 **Keywords:** Artificial upwelling; Carbon sink; Mariculture algae; Nutrient removal; Scenario analysis

23 **Highlights**

- 24 • Artificial upwelling shows potential for algae carbon sink and nutrient removal.
- 25 • Algae carbon sink and nutrient removal are limited by area and algal species.
- 26 • Artificial upwelling offsets adverse factors by boosting yield.
- 27 • Artificial upwelling has limitations in offsetting loss.

28 **1. Introduction**

29 Mariculture algae is an important component of marine ecosystems, and may deliver both economic and environmental
30 benefits. As the fourth species of blue carbon (IPCC, 2019), mariculture algae has been recognized as having capacity to
31 act as a carbon sink (Bolton and Stoll, 2013; Ahmed et al., 2017; Tsai et al., 2017; NASEM, 2021). Harvesting of algae
32 can also remove nitrogen (N) and phosphorus (P) from coastal waters (Alvera-Azcarate et al., 2003; Fei, 2004; He et al.,
33 2008; Xiao et al., 2017; Sinha et al., 2022), and has been proposed as an effective ecological restoration tool to control
34 eutrophication (Yang et al., 2015; Buschmann et al., 2017; Jiang et al., 2020). Further research is required on how to fully
35 exploit the function of mariculture algae in addressing climate change and marine pollution.

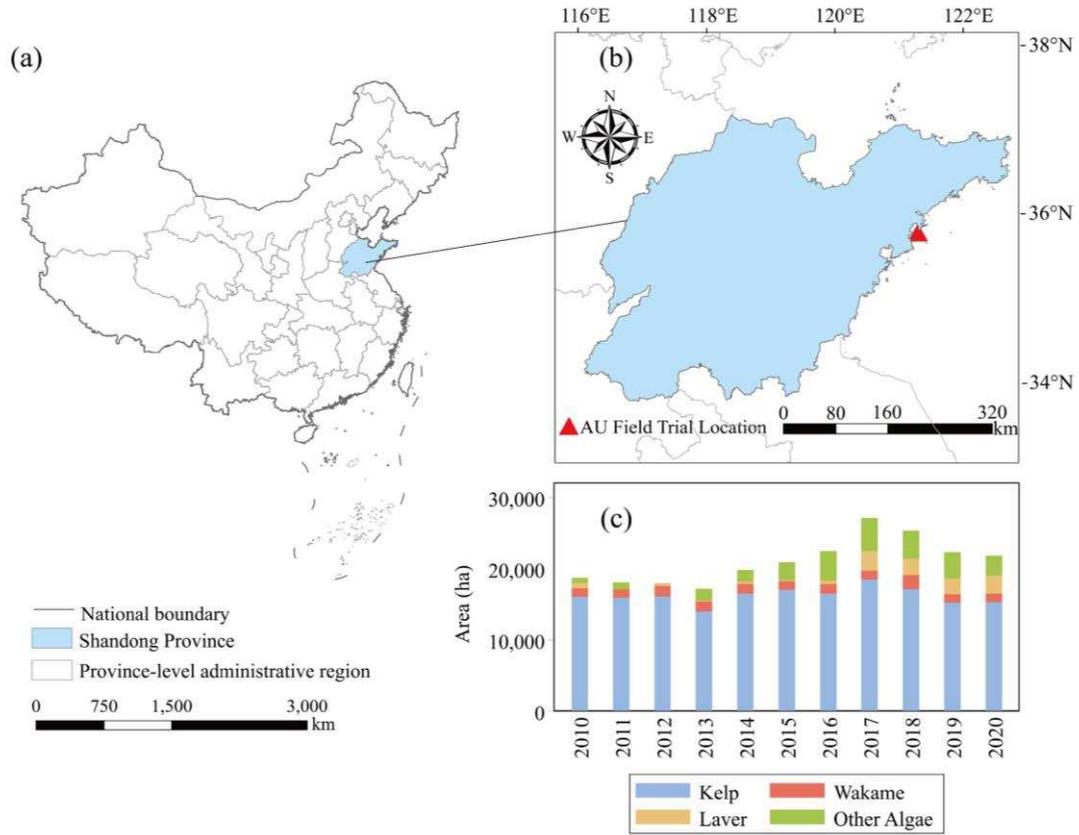
36 China leads the world in the production of mariculture algae (FAO, 2022), and has implemented a number of initiatives
37 to promote the development of algae derived carbon sinks (Jiao et al., 2018; Yang et al., 2021). Many scholars have found
38 an increase in the carbon sink of algae between 2010 and 2015 (Shao et al., 2019; Yang et al., 2022). These studies
39 recognize the major contribution of increased algae production to carbon sinks compared to the more limited effects of
40 algal species (Ren, 2021). Similar conclusions may be drawn for nitrogen and phosphorus removal by algae (Xiao et al.,
41 2017). However, algae derived carbon sink development has slowed in several of China's coastal provinces, despite the
42 growth of carbon sinks between 2010 and 2015 (Gu and Yin, 2022; Wu and Li, 2022; Yang et al., 2022). This decrease
43 in production growth has led to a significant slowdown in the growth of carbon sinks, which also affects the function of
44 algae in nutrient removal (Wu et al., 2017). Indeed, recent ocean warming, coastal pollution, competition for space, and
45 ecological policies to control eutrophication have limited the expansion of mariculture algae production (Filbee-Dexter
46 and Wernberg, 2018; Jouffray et al., 2020; Hu et al., 2021; Wang et al., 2023).

47 Previous studies have addressed that the changes in production predominantly affect algae derived carbon sinks and
48 nutrient removal. However, two key factors that influence changes in production, i.e. yield (production per area) and area,
49 have been rarely studied. First, increasing the yield could offset the negative effects on algae production. One of the
50 promising technics to enhance algae yield and subsequently increase algae derived carbon sinks is artificial upwelling
51 (AU), which has been shown to increase mariculture algal yield in small-scale trials (Fan et al., 2019; Lin et al., 2019;
52 Fan et al., 2020). AU is a system of mechanical equipment deployed in the mariculture area, which breaks the nutrient

53 limitations of aquaculture by continuously upwelling the lower temperature, higher nutrient loaded seawater to the surface
54 (Aure et al., 2007; Lovelock and Rapley, 2007; McClimans et al., 2010; Zollmann et al., 2019; Ortiz et al., 2022). AU in
55 nutrient-rich waters can enhance the biological carbon pump in oligotrophic sea areas to sequester anthropogenic carbon
56 dioxide (CO₂) and increase carbon sequestration (Oschlies et al., 2010; Pan et al., 2015; Gómez-Letona et al., 2022), and
57 has been recognized by the United Nations Intergovernmental Panel on Climate Change (IPCC) as a global ocean carbon
58 sink solution (IPCC, 2019). However, the potential of AU to offset the limitations on algae derived carbon sinks and
59 nutrient removal remains unknown. Second, the reduction in mariculture area limits production growth, which inevitably
60 affects the amount of algae derived carbon sinks and nutrient removal. However, no studies have yet been carried out to
61 examine area as a driving factor to changes of carbon sinks and nutrient removal. Therefore, we further decompose
62 mariculture production that predominantly affects algae derived carbon sinks and nutrient removal into two components
63 i.e., yield and area. From this we hope to explore how algal yield may be enhanced through AU under limited expansion
64 of mariculture area.

65 In this paper, we analyse the driving forces that constrain carbon sink growth and investigate the potential of AU in
66 offsetting these factors using Shandong Province, China (Fig. 1) as a case study. Shandong Province, which is bordered
67 by the Bohai Sea and the Yellow Sea, has a long coastline accounting for 1/6 of the total coastline of China (Jiao et al.,
68 2021). As China's most important mariculture location (Zhao et al., 2022), Shandong Province accounts for 27.28% (2020
69 base) of the country's mariculture algae production (SFSY, 2021). Moreover, multiple AU field experiments conducted
70 in Shandong Province analysed the specific enhancement effect of AU application, which provided the necessary
71 technical parameters for predicting the potential of AU (Fan et al., 2019; Lin et al., 2019).

72 Our study is distinct from previous studies by (a) decomposing production, a factor that leads to a decline in the annual
73 growth rates of carbon sinks and nutrient removal in recent years, into yield and area; (b) estimating the potential of AU
74 to enhance the yield and subsequently offset the loss of carbon sinks and nutrient removal caused by negative drivers;
75 and (c) exploring the upper limits of AU potential. [Our research thus identifies previously unaddressed limiting factors in
76 carbon sink growth and nutrient removal, which can be used to develop more targeted policies aimed at reversing the
77 resulting negative impacts. Meanwhile, this study informs a new technology pathway for increasing carbon sinks and
78 mitigating seawater eutrophication, i.e. applying AU, which can broaden the spectrum of policy and management tools
79 to address climate change and marine pollution. Our findings also suggest that enhancing mariculture algae derived carbon
80 sinks and nutrient removal is a complex and systematic work that requires consideration of multiple influencing factors
81 and their positive and negative effects.](#)



82
 83 **Fig. 1.** General information of the study area. (a) The location of Shandong Province in China; (b) AU field trial location in Shandong
 84 Province (36°22' N, 120°50' E); and (c) mariculture algae area and structure in Shandong Province between 2010 and 2020.

85 **2. Methodology and data**

86 **2.1. Measurement of carbon sink and nutrient removal of mariculture algae**

87 Algae take up CO₂ and dissolved inorganic carbon through photosynthesis as algae grow and convert it into organic
 88 carbon (Smith, 1981; Gao and McKinley, 1994). A portion of the organic carbon is removed from seawater after
 89 harvesting, forming the carbon sink of the algal body. In addition, algae also release some particulate organic carbon
 90 (POC) and dissolved organic carbon (DOC) into seawater (Tyler and McGlathery, 2006; Tang et al., 2011; Watanabe et
 91 al., 2020; Weigel and Pfister, 2021). A portion of POC and DOC will deposit in the deep ocean and seabed under microbial
 92 action to form stable sediments (Jiao et al., 2010). This fraction of sediments that can be stored for long periods is a carbon
 93 sink (Krause-Jensen and Duarte, 2016; Pan et al., 2019; Gao et al., 2021).

94 We calculated the carbon sink of mariculture algae (TC , assuming a total of i species) by adding three components
 95 (Yang et al., 2022) i.e., the carbon sink of the algal body (C_i), the carbon sink formed by releasing POC (C_i^{POC}), and the
 96 carbon sink formed by releasing DOC (C_i^{DOC}):

97
$$TC = \sum_{i=1}^n (C_i + C_i^{POC} + C_i^{DOC}) \quad (1)$$

98 When measuring the carbon sink of mariculture algae:

99 $C_i = DW_i \times w_i^C$ (2)

100 $C_i^{\text{POC}} = C_i \times \frac{\alpha}{1-\alpha-\beta} \times r^{\text{POC}}$ (3)

101 $C_i^{\text{DOC}} = C_i \times \frac{\beta}{1-\alpha-\beta} \times r^{\text{DOC}}$ (4)

102 The carbon sink of the mariculture algal body (C_i) can be estimated from algal production (dry weight) (DW_i) and the
 103 carbon (C) content of algae (w_i^C). α and β represent the proportion of POC and DOC released during algal growth to
 104 algal photosynthetic productivity (Yan et al., 2011). r^{POC} and r^{DOC} are the proportion of POC and DOC released by
 105 algae that are eventually converted into carbon sinks.

106 N and P removal by algae was determined by algal production (dry weight) and the N and P content of algae. The
 107 specific calculation formula is as follows:

108 $N_i = DW_i \times w_i^N$ (5)

109 $P_i = DW_i \times w_i^P$ (6)

110 Here, N_i and P_i represent N and P removal, w_i^N and w_i^P are the N and P content of the algae.

111 **2.2. Driving force analysis using the Logarithmic Mean Divisia Index approach**

112 We used the Logarithmic Mean Divisia Index (LMDI) method to decompose changes in carbon sinks and nutrient
 113 removal by mariculture algae. Proposed by Ang et al. (2004), the LMDI method employs a logarithmic transformation,
 114 which is an applicable method to quantify the drivers of a given variable without any residual terms after decomposition.
 115 Compared to other decomposition methods, the results obtained from LMDI decomposition are intuitive and easy to
 116 interpret (Nzudie et al., 2021), making it a valuable tool in various fields, including carbon emissions (Ma et al., 2003),
 117 energy intensity (Wang et al., 2005), and water footprint (Zhao et al., 2017). We identified four driving factors i.e.,
 118 intensity, yield, structure, and area, as shown in Eq. 7:

119 $M = \sum_{i=1}^n \frac{M_i}{DW_i} \times \frac{DW_i}{A_i} \times \frac{A_i}{A} \times A = \sum_{i=1}^n I_i \times Y_i \times S_i \times A$ (7)

120 Here, M represents the carbon sink or nutrient removal of mariculture algae; subscript i represents algal species i , and
 121 n represents the total number of algal species (for this study $n = 4$); DW_i represents the production of algal species i ;
 122 A_i is the mariculture area used for growth of algal species i ; A refers to the total mariculture area of algae. I , Y , S ,
 123 and A represent intensity, yield, structure, and area, respectively. Intensity is the amount of carbon sink or nutrient
 124 removal per unit of algal species i 's production. Yield describes the amount of production per unit of algal species i 's
 125 area. Structure is the ratio of algal species i 's area to the total area of all algae, representing the effect of algal species
 126 changes. Area reflects how the total area of mariculture algae can impact the carbon sink or nutrient removal of algal
 127 species i .

128 The total changes in the carbon sink or nutrient removal of mariculture algae can thus be formulated as:

129 $\Delta M = M^t - M^0 = \Delta I + \Delta Y + \Delta S + \Delta A$ (8)

130 where ΔI (intensity effect), ΔY (yield effect), ΔS (structure effect), and ΔA (area effect) are changing driving factors
 131 of ΔM .

132 The value of I_i depends on the C, N, and P content of algae, which varies in different mariculture areas and seasons.
 133 However, we do not consider the changes in these parameters in our measurement. Such setting is primarily because our
 134 focus was on studying the carbon sink of the algal body at the time of harvest. Changes in C, N and P content of algal
 135 body during the harvest season are relatively small (He et al. 2008; Xiao et al. 2017; Zhang et al. 2020). In the subsequent
 136 analysis, I_i remains unchanged and the contribution from the intensity effect (ΔI) to the increase in algae derived carbon
 137 sinks and nutrient removal amounts to 0.

138 According to the LMDI approach, the equations to decompose the changes to mariculture algae derived carbon sinks
 139 or nutrient removal are as follows:

140 $\Delta M_I = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{I_i^t}{I_i^0})]$ (9)

141 $\Delta M_Y = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{Y_i^t}{Y_i^0})]$ (10)

142 $\Delta M_S = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{S_i^t}{S_i^0})]$ (11)

143 $\Delta M_A = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{A_i^t}{A_i^0})]$ (12)

144 Where t and 0 represent the latter and former year during the change, respectively. L is the log-average function,
 145 which satisfies:

146 $L(M_i^t, M_i^0) = \frac{M_i^t - M_i^0}{\ln(M_i^t) - \ln(M_i^0)}, M_i^t \neq M_i^0$ (13)

147 $L(M_i^t, M_i^0) = M_i^t, M_i^t = M_i^0$ (14)

148 **2.3. Scenario setting**

149 To estimate the potential for AU to offset the limiting effects on algae derived carbon sinks and nutrient removal by
 150 2030, we set a No-AU scenario based on the development characteristics of previous mariculture area growth, as well as
 151 four scenarios that consider the application of AU. The LMDI analysis was intended to reveal the driving factors that
 152 slow down the carbon sink and nutrient removal growth between 2014 and 2020. Thus, we were interested in establishing
 153 whether applying AU can effectively mitigate these negative factors. In the AU application scenarios, we intended to
 154 calculate the minimum percentage of areas where AU application can compensate for reducing carbon sinks (nutrient
 155 removal). We assumed that the yield of mariculture algae can increase by a factor of μ when applying AU. Our study
 156 aimed to determine the minimum AU application proportions required to achieve a comparable scale of carbon sink

157 (nutrient removal) as in the No-AU scenario by 2030 in the four AU application scenarios, namely λ_1 (scenario S1), λ_2
158 (scenario S2), λ_3 (scenario S3), and λ_4 (scenario S4). Between 2021 and 2030, AU would be applied annually in $\lambda/10$
159 of the mariculture area. The yield of mariculture algae in Shandong Province in 2030 would be $Y_{2020}(1 + \lambda \cdot \mu)$. The
160 details of the scenarios were as follows:

161 **No-AU scenario (N1).** In the No-AU scenario, the average annual change rates of the algal area between 2021 and
162 2030 remained consistent with the average change rates of the area between 2010 and 2020. The algal structure and yield
163 remain unchanged at 2020 levels.

164 **Area constant scenario (S1).** We assumed the mariculture area of algae remained at 2020 levels. The structure of algal
165 species would be the same as for the No-AU scenario. By 2030, the algal yield would be $Y_{2020}(1 + \lambda_1 \cdot \mu)$.

166 **Area reduction scenario (S2).** There has been a noticeable decline in the mariculture area in Shandong Province since
167 2017. Hence, this scenario assumed that future changes in the mariculture area would maintain this trend. Specifically,
168 the mariculture area continued to decrease between 2021 and 2030 at an average change rate to that observed between
169 2017 and 2020, while the algal structure would remain unchanged based on 2020 levels. By 2030, the algal yield would
170 be $Y_{2020}(1 + \lambda_2 \cdot \mu)$.

171 **Laver increase scenario (S3).** The contribution of algae to carbon sinks and mitigation of seawater eutrophication
172 varies with algal species (Zheng et al., 2019). The increase in the area proportion of laver will have a negative impact on
173 the growth of carbon sinks (nutrient removal). We therefore assumed that the area proportion of laver would continue to
174 increase by 2030, at a mean growth rate to that observed between 2010 and 2020, while the mariculture area was the same
175 as in the No-AU scenario. By 2030, algal yield would therefore be $Y_{2020}(1 + \lambda_3 \cdot \mu)$.

176 **Area reduction and laver increase scenario (S4).** The area given over to mariculture algal growth would be consistent
177 with scenario S2, and the algal structure would be consistent with scenario S3. We would also calculate the minimum
178 application ratio λ_4 of AU in order to achieve a comparable scale of carbon sink (nutrient removal) as in the No-AU
179 scenario.

180 **2.4. Uncertainty and sensitivity test**

181 In this study, we utilized a Monte Carlo simulation to estimate the uncertainties in carbon sink and nutrient removal of
182 mariculture algae. The overall uncertainty is calculated under the 95% confidence interval around the arithmetic mean.
183 The distribution characteristics of specific model parameters are shown in Table A1. Additionally, we performed a
184 sensitivity test for the carbon sink and nutrient removal of mariculture algae to analyse the impact of different input
185 parameters on the model outputs.

186 **2.5. Data collection**

187 We obtained data on the production and area of mariculture algae from the "Shandong Fishery Statistical Yearbook"
 188 (SFSY, 2011-2021). The specific biological parameters are shown in Table 1. The main mariculture algal species in
 189 Shandong Province were kelp, laver, and wakame, which together contributed approximately 90% of total production.
 190 Therefore, in the following study, the mariculture algae in Shandong Province were divided into four categories i.e., kelp,
 191 laver, wakame, and others.

Table 1
 Biological parameters of mariculture algae (%).

Species	Carbon content of algae (w_i^C)	Nitrogen content of algae (w_i^N)	Phosphorus content of algae (w_i^P)
Kelp	24.99	3.71	0.52
Laver	29.09	6.30	1.00
Wakame	30.48	5.01	0.76
Other algae	28.19	5.01	0.76

Notes: The C content ratio of kelp, laver, and wakame refer to Zhang et al. (2020). The C content of other algae species were taken as the mean values of kelp, laver, and wakame. The N and P content of kelp refer to Xiao et al. (2017). The N and P content of laver refer to He et al. (2008). Other algal species' N and P contents were taken as the mean values of kelp and laver.

192 Other parameters are shown in Table 2. We extract the parameters related to carbon sink formation from field studies
 193 and experimental data available in the literature. Consistent with the study by Yan et al. (2011), we adopt the values of
 194 α and β as 0.19 and 0.05, respectively (Khailov and Burlakova, 1969; Penhale and Capone, 1981; Yoshikawa et al.,
 195 2001). While previous studies have considered the carbon sink formed by releasing POC and DOC (Yan et al., 2011;
 196 Yang et al., 2022), field investigations have revealed that not all POC and DOC deposited on the seafloor contribute to
 197 carbon sink formation (Nelson et al., 2002; Jiao et al., 2010; Baetge et al., 2020). Nilsson et al. (2018) demonstrated that
 198 only 4% of the POC in the Baltic Sea was deposited on the seafloor to form carbon sinks. Chen et al. (2020) found that
 199 only 1.6% of the DOC released by algae remained unaltered by microorganisms and stably persisted in seawater. Hence,
 200 we assign the values of 0.04 and 0.016 to the parameters r^{POC} and r^{DOC} , respectively.

201

Table 2

The mechanism parameters of carbon sink of mariculture algae.

Mechanism parameters	Values	References
α	0.19	Yoshikawa et al. (2001); Yan et al. (2011)
β	0.05	Penhale and Capone (1981); Yan et al. (2011)
r^{POC}	0.04	Nilsson et al. (2018); Nelson et al. (2002)
r^{DOC}	0.016	Jiao et al. (2010); Chen et al. (2020)

202 The value of the average promotion rate on yield of AU (μ) was based on previous field experiments. Fan et al. (2019)
 203 compared 60 strains of algae from the distribution area of the AU system and an area remote from the AU system. They
 204 found that AU increased the average weight per algae by approximately 109.9%. Lin et al. (2019) found that the average
 205 weight of algae in the experimental group grown around the AU area was 33.1g, while the average weight of algae in the
 206 control group grown in the natural environment was 10.1g. Based on the above findings, we took a μ of 1.1 to ensure the
 207 reliability of the prediction results.

208 3. Results

209 3.1. Carbon sink and nutrient removal of mariculture algae between 2010 and 2020

210 Between 2010 and 2020, the average annual carbon sink of mariculture algae in Shandong Province was 162.20 kt,
 211 representing 23.14% of the carbon emissions of marine fisheries in 2014 (Yue et al., 2016). The carbon sink in the algal
 212 body accounted for 98.91% of the total mariculture algae derived carbon sinks, while the carbon sink formed via releasing
 213 POC and DOC contributed only 1.09%. The proportion of carbon sinks formed by POC and DOC measured in this study
 214 was lower than in other studies due to the lower r^{POC} and r^{DOC} values utilised (Yan et al., 2011; Yang et al., 2022).

215 The carbon sink of mariculture algae in Shandong Province showed an increasing trend between 2010 and 2020 (Table
 216 3), with an overall rate of 28.76%. The changes in carbon sinks may be divided into two distinct periods: from 2010 to
 217 2014, the average annual growth rate of mariculture algae derived carbon sink was 5.98%. While the average annual
 218 growth rate between 2014 and 2020 was only 0.34%.

219 The N and P removal trends are similar to those observed for carbon sinks. Specifically, between 2010 and 2014, there
 220 was a significant increase in N and P removal, with a rise of 26.78% and 27.49%, respectively. In contrast, the nutrient
 221 removal by mariculture algae was relatively stable between 2014 and 2020, with a modest increase of only 4.12% and
 222 4.85%, respectively.

223

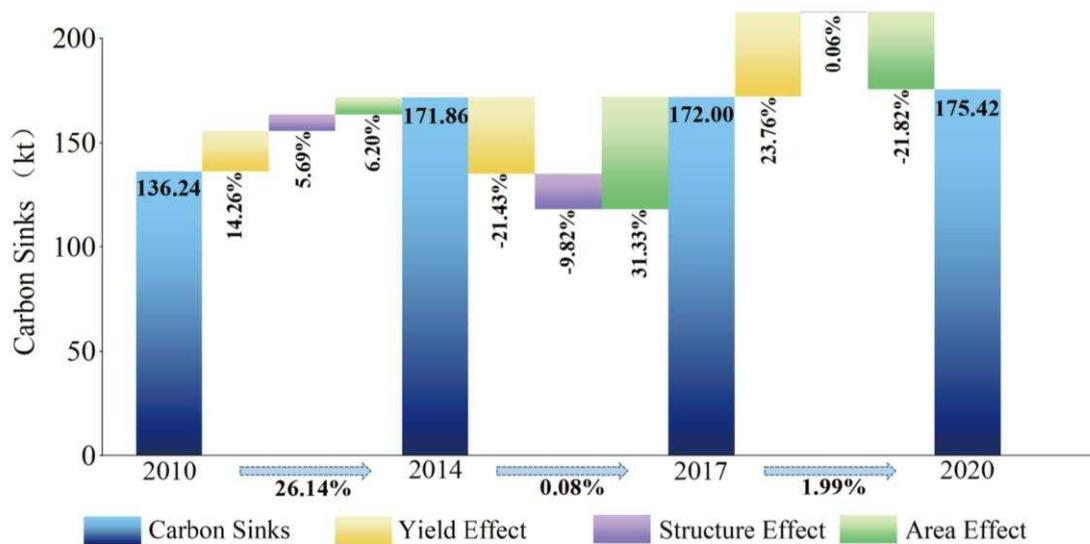
Table 3
The carbon sink and nutrient removal of mariculture grown algae in Shandong Province (kt).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Carbon sinks of algae body	134.75	129.58	145.69	151.04	169.98	170.75	173.67	170.12	172.81	172.76	173.51
Carbon sinks through POC	1.35	1.30	1.46	1.51	1.70	1.71	1.74	1.70	1.73	1.73	1.74
Carbon sinks through DOC	0.14	0.14	0.15	0.16	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Carbon sinks	136.24	131.01	147.30	152.71	171.86	172.64	175.59	172.00	174.72	174.67	175.42
Nitrogen Removal	20.50	19.76	22.28	23.09	25.99	26.12	26.79	26.31	26.94	27.18	27.06
Phosphorus Removal	2.91	2.81	3.18	3.29	3.71	3.73	3.84	3.77	3.88	3.93	3.89

224 **3.2. Driving force analysis for carbon sink and nutrient removal of mariculture algae**

225 We explored the driving factors (yield, structure, and area) leading to changes in carbon sink and nutrient removal of
 226 mariculture algae during the study period (Fig. 2). The analysis was divided into three periods: 2010-2014, 2014-2017,
 227 and 2017-2020. This division was based on the differences observed in the growth rates of carbon sinks and nutrient
 228 removal around 2014, as well as the clear downward trend in mariculture area used for algal growth since 2017.

229 Between 2010 and 2014 all three factors, i.e., yield, structure, and area, contributed to a rise in carbon sinks, resulting
 230 in a 26.14% increase in the carbon sink of algae relative to 2010. The yield effect stood out as the primary cause for
 231 increased carbon sinks (contributing 14.26% of the increase). Between 2014 and 2017, carbon sinks only increased by
 232 0.08% based on the 2014 level, and the effect of area became the major contributor to increased carbon sinks (53.84 kt,
 233 31.33%). In contrast, yield and structure showed inhibitory effects, resulting in a 21.43% and 9.82% reduction in carbon
 234 sinks, respectively. Between 2017 and 2020, the yield effect (40.87 kt, 23.76%) contributed positively to carbon sink
 235 growth, which was mostly offset by the negative effects of area (37.53 kt, 21.82%), resulting in only a slight increase in
 236 algae derived carbon sinks (1.99%). Meanwhile, the structure effect had little impact on carbon sinks (0.10 kt, 0.06%).
 237 The driving factors for N and P removal from mariculture algae in Shandong Province were similar to those found for
 238 carbon sinks (Fig. S1).



239

240 **Fig. 2.** Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt). The intensity effect
 241 (ΔI) is set to 0 and not shown in the figure.

242 We found driving force effects coincided with changes to the marine environment and policy adjustments. Prior to
 243 2014, production, area, and yield of mariculture algae in Shandong Province grew rapidly, encouraged by policies such
 244 as increased investment in marine fishery fixed assets, subsidising of fisheries diesel, and supporting fisheries resources
 245 protection (Liang et al., 2018; Han and Jiang, 2019). At the end of 2016, China released the 13th Five-Year Plan of
 246 National Fishery Development, which emphasized the implementation of coastal ecological protection and promoted
 247 structural reform on the supply side of fisheries (Cao et al., 2017; Su et al., 2021). As a result, many policies began to
 248 restrict the expansion of mariculture areas. For example, the Blue Bay Remediation Project (BBRP) was one of the major
 249 marine projects in China's 13th Five-Year Plan for ecological environmental protection, with Rizhao, Yantai, Weihai, and
 250 Qingdao in Shandong Province being selected as participating cities in early 2017. The project restricted or banned certain
 251 aquaculture activities in near-shore waters and targeted algal rafts for cleanup (Liu et al., 2019; Wang et al., 2020). In
 252 addition, several ecological policies, such as the "returning ponds to natural wetlands", have been implemented in some
 253 coastal aquaculture regions, leading to a significant decline in the mariculture algae area (Wang et al., 2023).

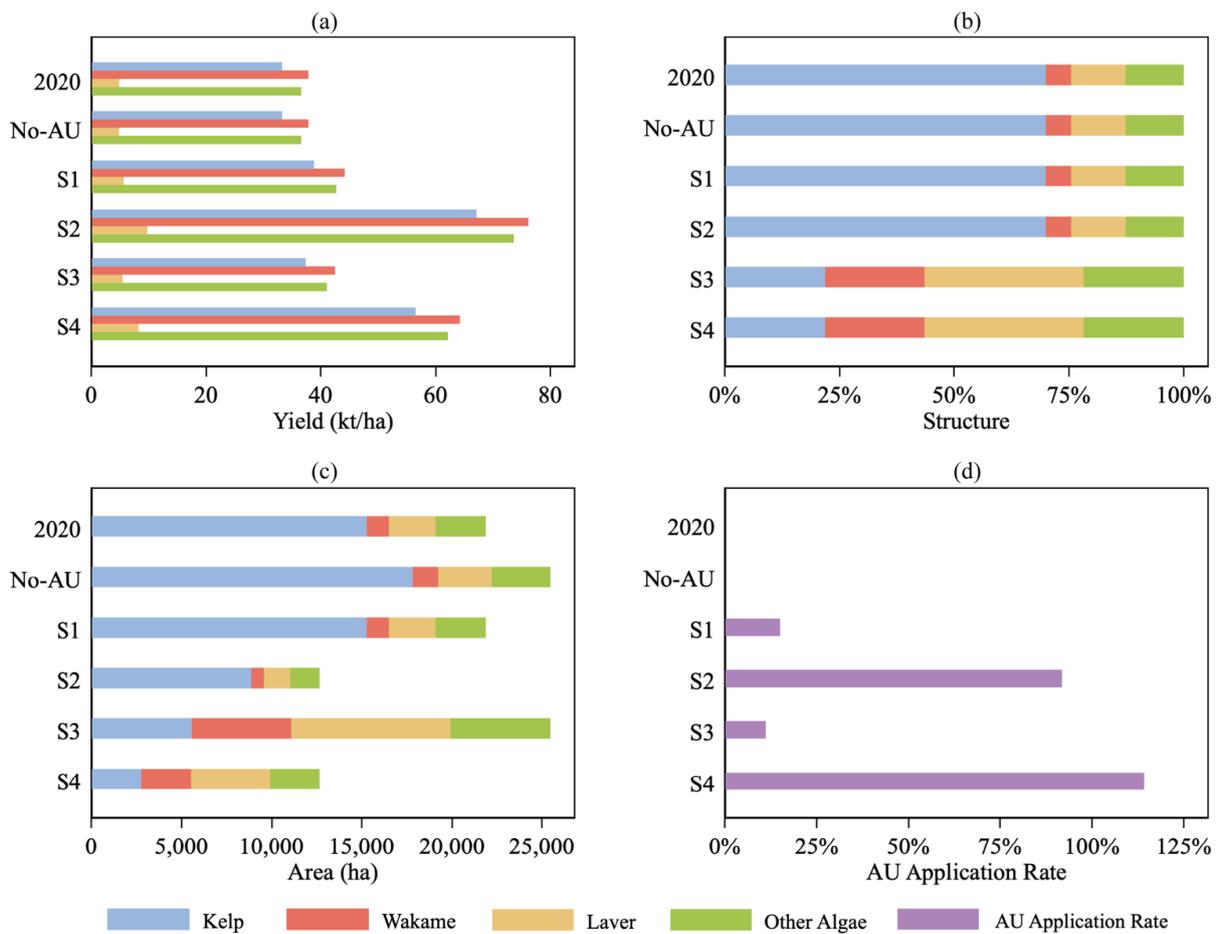
254 The yield effect showed a fluctuant trend between 2010 and 2020. This might be because artificial inputs and immature
 255 mariculture techniques dominated algae farming, which makes algal yield susceptible to extreme natural disasters,
 256 environmental conditions, water quality, and diseases (Zhang and Han, 2017).

257 The negative structural effect was primarily attributed to the increased share of laver in the mariculture area, as the
 258 carbon sink and nutrient removal per unit area of laver were less than 1/5 that of kelp and wakame. The share of laver
 259 increased from 1.34% to 11.80% during 2014-2020. The growing market demand for laver, a nutritious and healthy food
 260 (Brown et al., 2014), is causing the area of laver to expand. Meanwhile, rising seawater temperatures due to global

261 warming have led to disease outbreaks in Jiangsu Province, China's primary laver producing area, which led to many
 262 mariculture companies turning to promote the cultivation and demonstration of the laver in Shandong Province (Lu et al.,
 263 2022).

264 **3.3. Scenario analysis of the potential of AU for algae derived carbon sink and eutrophication mitigation**

265 We conducted a scenario analysis to evaluate the extent to which AU can offset the effects of two negative factors i.e.,
 266 area reduction and a more laver-oriented mariculture algal system. Fig. 3 shows the required application ratio of AU and
 267 the algal yield, structure, and area in 2030 to achieve the same carbon sink level as the No-AU scenario under different
 268 scenarios.



269 **Fig. 3.** Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030. The No-AU Scenario (No-AU) represents
 270 the case in which the mariculture algal area will grow at an average growth rate between 2010 and 2020, with structure and yield
 271 remaining unchanged from 2020 levels. Scenarios 1-4 (S1-S4) represent constant area scenarios, area reduction scenarios, increased
 272 laver scenario, and area reduction and laver increase scenarios, respectively.
 273

274 In the No-AU scenario, the algal area will continue to increase at an average annual growth rate between 2010 and
 275 2020, with the structure remaining consistent with the 2020 level. When no AU technology is applied, the carbon sink of

276 mariculture algae in Shandong Province will reach 204.41 kt by 2030, with corresponding N and P removal of 31.53 kt
277 and 4.54 kt, respectively.

278 Applying AU may compensate for the loss of carbon sink due to diminishing mariculture area and laver-oriented
279 structural change. In scenario S1, where the mariculture area and structure of algae remain unchanged at 2020 levels,
280 applying AU to 15.02% of the mariculture area was sufficient to achieve the same carbon sink level as in the No-AU
281 scenario by 2030. However, when the mariculture area decreases at the same rate as observed between 2017 and 2020
282 (scenario S2), AU would need to be applied to 91.81% of the area. In scenario S3, we assumed that the mariculture algal
283 area would maintain the same growth as for the No-AU scenario, while the proportion of laver would grow to 34.53% by
284 2030. In this case, applying an AU to 11.14% of the mariculture algal area would be necessary.

285 It is worth noting there is also a limit to the potential of AU to increase carbon sinks. AU will not fully compensate for
286 the negative effects of continuous mariculture area decline and the increase in the proportion of laver area (scenario S4).
287 We found that when AU was implemented across the entire mariculture area by 2030, it would compensate at most for a
288 carbon sink reduction of 44.52% in mariculture algal area compared to 2020, assuming algal structure remained constant.
289 Similarly, supposing the mariculture area was maintained at 2020 levels with 100% application of AU, the loss of carbon
290 sinks would not be compensated for when the share of laver exceeded 72.57%.

291 Applying AU can also compensate for the reduction in N and P removal due to mitigation in algal area and an increase
292 in the amount of laver (see Table A2). In the area reduction scenario (scenario S2), 96.23% and 95.46% of the area would
293 require AU application to secure identical N and P removal, respectively, as for the No-AU scenario by 2030. However,
294 the potential of AU would reach its limit when the area declined by more than 44.52% of the 2020 level. In the increased
295 laver scenario (scenario S3), where the laver area share increased to 34.53%, AU application rates would be 3.82% and
296 0.08% for N and P removal, respectively. If the share of laver exceeded 78.89% and 81.58%, achieving the same N and
297 P removal, respectively, as in the No-AU scenario then applying AU alone would no longer be feasible.

298 **4. Discussion**

299 ***4.1. Improving key factors that influence carbon sinks and nutrient removal***

300 China has acknowledged the importance of ocean carbon sinks, particularly algae derived carbon sinks, in mitigating
301 climate change (Yang et al., 2021). The country has laid out a policy system to support the development of ocean carbon
302 sinks around the goal of carbon peak and carbon neutrality. Despite the importance of algae for increasing carbon sinks
303 and achieving carbon neutrality, the incremental carbon sinks of algae have been limited in recent years (Gu and Yin,
304 2022; Wu and Li, 2022; Yang et al., 2022). In this study, we identified the main limiting factors of algae derived carbon
305 sinks and their contributions by proposing driving factors such as yield, structure, and area. Unlike the results of previous
306 studies (Shao et al., 2019; Ren, 2021; Yang et al., 2022), we demonstrated the importance of taking area into account as

307 a driving force. The results showed that area was the most critical factor driving the growth of algae derived carbon sinks
308 until 2017. However, between 2017 and 2020, decreasing area had a significant inhibitory effect on carbon sinks. Our
309 study also revealed the negative impacts of laver expansion and unstable yields on carbon sinks. The biased mariculture
310 algae structure of laver hindered the growth of carbon sinks, and yields that fluctuate significantly over time are less
311 conducive to the stable enhancement of carbon sinks. We found similar conclusions regarding influencing factors for N
312 and P removal. The findings have contributed to adjusting mariculture industry policies regarding improved area, structure,
313 and yield to support the growth of mariculture algae derived carbon sink and nutrient removal.

314 To guarantee a steady increase in algae derived carbon sinks and nutrient removal, we propose the application of AU
315 in mariculture areas. AU provides a new impetus to the growth of algae derived carbon sinks and nutrient removal by
316 increasing yield against the negative impacts of area constraint and changes in structure changes. Our research
317 investigated the potential for AU to offset these negative effects. The results showed that enhancing carbon sink and
318 nutrient removal through AU is feasible. However, the promotion of AU also faces challenges, including its low energy
319 efficiency and high installation costs (Fan et al., 2013; Viudez et al., 2016; Qiang et al., 2018). These challenges need to
320 be considered in successful implementation of AU technology and achievement of better results in Shandong Province
321 and other coastal areas. Using clean energy to achieve self-powered AU is crucial in application of AU (Pan et al., 2018),
322 and can effectively reduce energy consumption and greenhouse gas emissions. Specifically, offshore wind, solar and tidal
323 energy can be harnessed for in-situ power generation, while wave or ocean current energy can be utilized to drive
324 upwelling and further optimize energy efficiency. Meanwhile, AU may benefit from special subsidies, tax breaks, and
325 technology research support for blue carbon. Government and market instruments can be used to provide technical and
326 financial support for AU application and promotion.

327 The yield effect was unstable between 2010 and 2020, partially due to the dominance of immature mariculture
328 techniques that make algal yield susceptible to natural disasters, environmental conditions, and disease (Zhang and Han,
329 2017). Whether AU can solve or mitigate yield fluctuation problem remains unknown. To achieve an increased and steady
330 yield, AU could combine with other farming techniques, for example: (a) use of remote sensing technology and marine
331 monitoring technology to plan cultivation sites according to required environmental conditions for the growth of different
332 algal species (Ai et al., 2023); (b) developing integrated multi-trophic aquaculture (IMTA) and using interactions between
333 aquatic plants and animals at different trophic levels to improve mariculture efficiency (Cutajar et al., 2022; Hargrave et
334 al., 2022); and (c) genetic improvements, such as developing adaptable and disease-resistant algal cultivars (Hu et al.,
335 2021).

336 Notably, there is an upper limit to the benefits achieved through AU. Where mariculture area declines, or the proportion
337 of laver increases, applying AU may not achieve the desired carbon sink and nutrient removal levels. Currently,
338 mariculture grown algae in China is mainly associated with nearshore waters, and some mariculture areas have been

339 reduced or removed due to global climate change, seawater pollution, and policy requirements (Liu et al., 2019; Wang et
340 al., 2020). To solve this dilemma, focusing on pollution control and ecological restoration in the original nearshore
341 mariculture areas will help improve existing farming areas. In addition, offshore mariculture may be developed by
342 cultivating new species suitable for deep-water mariculture and developing new facilities to expand mariculture space.
343 We've also noticed farmers tend to prioritize economic value of algae over environmental function when selecting species
344 for cultivation (Zheng et al., 2019). Laver is more economically valuable and preferred by farmers, while kelp and wakame
345 have a higher carbon sink and nutrient removal rates per unit of farmed area (Ou et al., 2017). By establishing marine
346 carbon sink trading platforms, farmers can be encouraged and guided to grow more species with high carbon sinks to
347 convert algae with high carbon sink functions from resources to assets. As a result, market players who protect and restore
348 the ecological environment can receive reasonable returns.

349 **4.2. Limitations**

350 As with all studies of this nature there are some limitations to our work: (a) we have simplified the complexities of
351 market demand on mariculture algal production. Total algae production may not increase even with productivity-
352 enhancing techniques because the total demand may remain relatively constant; (b) AU works better for areas where
353 surface seawater is nutrient-poor (Fan et al., 2020). The percentage increase in acreage from AU (μ) may vary depending
354 on nutrient salt levels in different waters; (c) AU can increase carbon sink conversion efficiency by enhancing the
355 downward fluxes of POC (Baumann et al., 2021). We have not considered this effect in our projections of AU potential
356 due to a lack of robust and relevant parameters. The effect of AU may potentially increase the carbon sink formed by both
357 POC and DOC, providing an even more significant environmental benefit.

358 A point that needs to be emphasised is that as a geo-environmental project, applying AU may potentially have adverse
359 effects on the marine environment, particularly when implemented extensively in deep-sea areas (Ryan et al., 2009; Keller
360 et al., 2014; Kwiatkowski et al., 2015; Pan et al., 2016). However, in our scenario analysis, AU will be deployed in areas
361 designated for mariculture algae. Algae typically thrive in shallow coastal regions, and applying AU in these mariculture
362 algae areas away from the deep sea will not greatly impact the environment (Maruyama et al., 2004). Meanwhile, AU's
363 efficiency is also characterized by certain technical parameters, such as power demand (Pan et al., 2018). Using non-clean
364 energy-powered AU may partly offset its environmental benefits. Fortunately, recent field experiments have demonstrated
365 the feasibility of solar-powered AU (Fan et al., 2020). The energy efficiency of AU will continue to improve with the
366 development of energy management technology (Lin et al., 2019).

367 Our measurements of the carbon sink of mariculture algae were based on numerical models and parameters. In contrast
368 to previous studies (Yan et al., 2011; Ren, 2021; Yang et al., 2022), our measurement of carbon sink in algae considers
369 not only the carbon sink of the algal body but also POC and DOC, which allows us to capture the full extent of carbon

370 sequestration by the algae. In addition, the fact that only a small portion of POC and DOC contribute to the formation of
371 carbon sink is also considered (Nelson et al., 2002; Nilsson et al., 2018; Chen et al., 2020). We further analysed the
372 sensitivity of our results to the parameters r^{POC} , r^{DOC} , α , and β to test the robustness of our results. The detailed
373 results of the sensitivity test are shown in Table A3. The results showed that the carbon sink of mariculture algae will
374 increase by 0.018% to 0.129% in 2020 if the mechanism parameters were increased by 10%. We also estimated the
375 uncertainties of model parameters using Monte Carlo simulation methods. The uncertainty ranges of the carbon sink of
376 mariculture algae between 2010 and 2020 are presented in Fig. A.2. The uncertainty of carbon sinks (expressed as relative
377 standard deviation (RSD) that equals the standard deviation divided by the mean) ranged from 7.64% to 9.63%, indicating
378 that the results were reliable. However, the N and P removal uncertainties were relatively high, ranging from 21.31% to
379 26.56%, and 27.90% to 35.13%, respectively, which was due to the lack of precision and relatively large standard
380 deviation in the results of existing studies regarding the measurement of algal N and P content.

381 **5. Conclusions**

382 This study focused on exploring the potential of AU to enhance algae derived carbon sink and mitigate eutrophication
383 in the face of continued mariculture area degradation and undesired structural change. The limited growth of the
384 mariculture algae area in Shandong Province, China, and the more intensive cultivation of laver in the limited area has
385 resulted in minimal improvements in carbon sinks and nutrient removal levels since 2014. Our findings indicated that
386 applying AU could effectively compensate for the loss of carbon sink and nutrient removal caused by the decrease of
387 mariculture area or the increase of the laver share. Meanwhile, we observed that the potential for AU to achieve these
388 benefits has upper limits. It is worth mentioning that scenario analysis cannot calculate future carbon sinks and nutrient
389 removal accurately, but rather reflects a promising technical pathway for improving algae derived carbon sinks and
390 nutrient removal in the face of shrinking mariculture areas and suboptimal species selection. Further research could
391 investigate the implication of other potential variables, such as the intensity effect changes over time and AU energy
392 efficiency on the carbon sink and nutrient removal potential.

393 **CRedit authorship contribution statement**

394 **Chunlei Shen:** Conceptualization, Writing – original draft, Investigation, Formal analysis. **Xinya Hao:**
395 Conceptualization, Methodology, Software, Writing – review & editing. **Dong An:** Investigation, Data curation. **Martin**
396 **R. Tillotson:** Writing – original draft, Writing – review & editing. **Lin Yang:** Conceptualization, Supervision,
397 Investigation, Funding acquisition. **Xu Zhao:** Conceptualization, Writing – review & editing, Methodology, Funding
398 acquisition.

399 **Declaration of competing interest**

400 The authors declare that they have no known competing financial interests or personal relationships that could have
401 appeared to influence the work reported in this paper.

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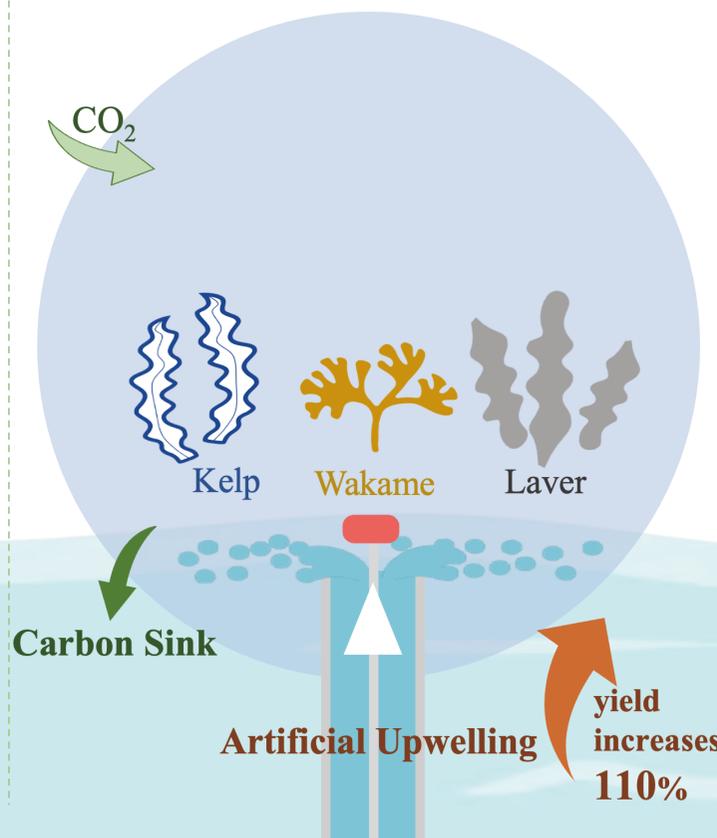
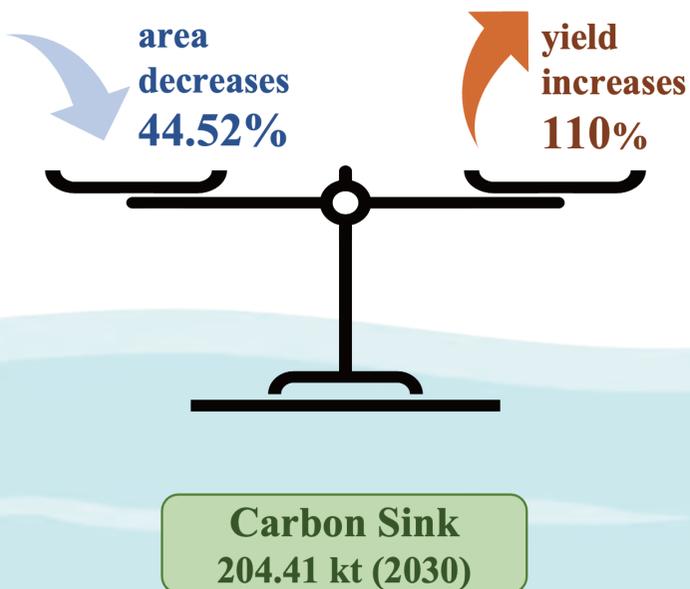
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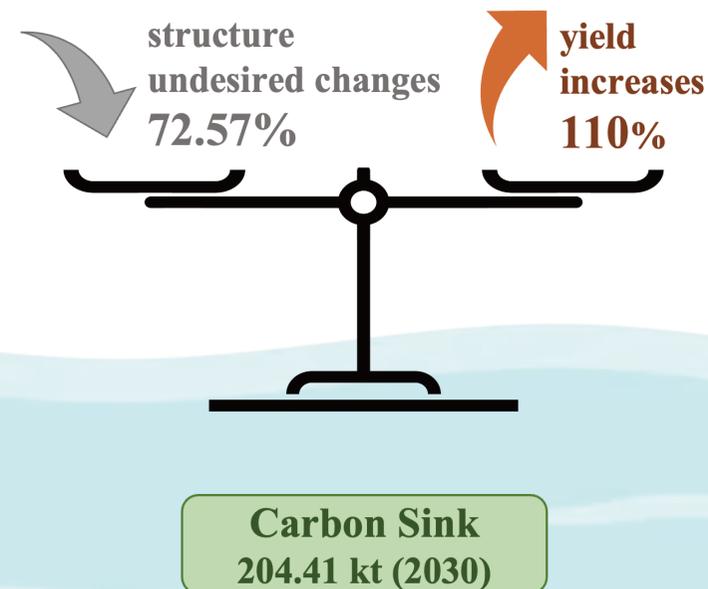
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Unraveling the potential of artificial upwelling (AU) for algae derived carbon sink and eutrophication mitigation

Applying AU Offsets
Area Decrease



Applying AU Offsets
Undesired Structural Change



Highlights

- Artificial upwelling shows potential for algae carbon sink and nutrient removal.
- Algae carbon sink and nutrient removal are limited by area and algal species.
- Artificial upwelling offsets adverse factors by boosting yield.
- Artificial upwelling has limitations in offsetting loss.

22 **Keywords:** Artificial upwelling; Carbon sink; Mariculture algae; Nutrient removal; Scenario analysis

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28 **1. Introduction**

29 Mariculture algae is an important component of marine ecosystems, and may deliver both economic and environmental
30 benefits. As the fourth species of blue carbon (IPCC, 2019), mariculture algae has been recognized as having capacity to
31 act as a carbon sink (Bolton and Stoll, 2013; Ahmed et al., 2017; Tsai et al., 2017; NASEM, 2021). Harvesting of algae
32 can also remove nitrogen (N) and phosphorus (P) from coastal waters (Alvera-Azcarate et al., 2003; Fei, 2004; He et al.,
33 2008; Xiao et al., 2017; Sinha et al., 2022), and has been proposed as an effective ecological restoration tool to control
34 eutrophication (Yang et al., 2015; Buschmann et al., 2017; Jiang et al., 2020). Further research is required on how to fully
35 exploit the function of mariculture algae in addressing climate change and marine pollution.

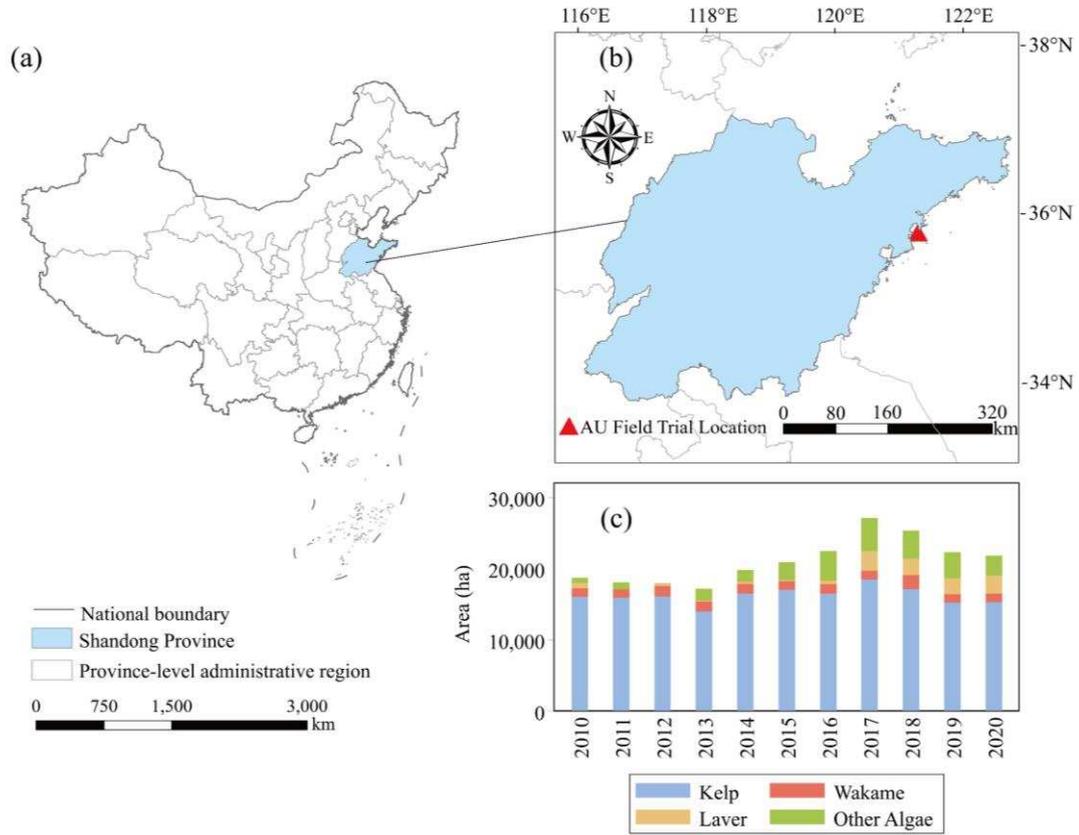
36 China leads the world in the production of mariculture algae (FAO, 2022), and has implemented a number of initiatives
37 to promote the development of algae derived carbon sinks (Jiao et al., 2018; Yang et al., 2021). Many scholars have found
38 an increase in the carbon sink of algae between 2010 and 2015 (Shao et al., 2019; Yang et al., 2022). These studies
39 recognize the major contribution of increased algae production to carbon sinks compared to the more limited effects of
40 algal species (Ren, 2021). Similar conclusions may be drawn for nitrogen and phosphorus removal by algae (Xiao et al.,
41 2017). However, algae derived carbon sink development has slowed in several of China's coastal provinces, despite the
42 growth of carbon sinks between 2010 and 2015 (Gu and Yin, 2022; Wu and Li, 2022; Yang et al., 2022). This decrease
43 in production growth has led to a significant slowdown in the growth of carbon sinks, which also affects the function of
44 algae in nutrient removal (Wu et al., 2017). Indeed, recent ocean warming, coastal pollution, competition for space, and
45 ecological policies to control eutrophication have limited the expansion of mariculture algae production (Filbee-Dexter
46 and Wernberg, 2018; Jouffray et al., 2020; Hu et al., 2021; Wang et al., 2023).

47 Previous studies have addressed that the changes in production predominantly affect algae derived carbon sinks and
48 nutrient removal. However, two key factors that influence changes in production, i.e. yield (production per area) and area,
49 have been rarely studied. First, increasing the yield could offset the negative effects on algae production. One of the
50 promising technics to enhance algae yield and subsequently increase algae derived carbon sinks is artificial upwelling
51 (AU), which has been shown to increase mariculture algal yield in small-scale trials (Fan et al., 2019; Lin et al., 2019;
52 Fan et al., 2020). AU is a system of mechanical equipment deployed in the mariculture area, which breaks the nutrient

53 limitations of aquaculture by continuously upwelling the lower temperature, higher nutrient loaded seawater to the surface
54 (Aure et al., 2007; Lovelock and Rapley, 2007; McClimans et al., 2010; Zollmann et al., 2019; Ortiz et al., 2022). AU in
55 nutrient-rich waters can enhance the biological carbon pump in oligotrophic sea areas to sequester anthropogenic carbon
56 dioxide (CO₂) and increase carbon sequestration (Oschlies et al., 2010; Pan et al., 2015; Gómez-Letona et al., 2022), and
57 has been recognized by the United Nations Intergovernmental Panel on Climate Change (IPCC) as a global ocean carbon
58 sink solution (IPCC, 2019). However, the potential of AU to offset the limitations on algae derived carbon sinks and
59 nutrient removal remains unknown. Second, the reduction in mariculture area limits production growth, which inevitably
60 affects the amount of algae derived carbon sinks and nutrient removal. However, no studies have yet been carried out to
61 examine area as a driving factor to changes of carbon sinks and nutrient removal. Therefore, we further decompose
62 mariculture production that predominantly affects algae derived carbon sinks and nutrient removal into two components
63 i.e., yield and area. From this we hope to explore how algal yield may be enhanced through AU under limited expansion
64 of mariculture area.

65 In this paper, we analyse the driving forces that constrain carbon sink growth and investigate the potential of AU in
66 offsetting these factors using Shandong Province, China (Fig. 1) as a case study. Shandong Province, which is bordered
67 by the Bohai Sea and the Yellow Sea, has a long coastline accounting for 1/6 of the total coastline of China (Jiao et al.,
68 2021). As China's most important mariculture location (Zhao et al., 2022), Shandong Province accounts for 27.28% (2020
69 base) of the country's mariculture algae production (SFSY, 2021). Moreover, multiple AU field experiments conducted
70 in Shandong Province analysed the specific enhancement effect of AU application, which provided the necessary
71 technical parameters for predicting the potential of AU (Fan et al., 2019; Lin et al., 2019).

72 Our study is distinct from previous studies by (a) decomposing production, a factor that leads to a decline in the annual
73 growth rates of carbon sinks and nutrient removal in recent years, into yield and area; (b) estimating the potential of AU
74 to enhance the yield and subsequently offset the loss of carbon sinks and nutrient removal caused by negative drivers;
75 and (c) exploring the upper limits of AU potential. Our research thus identifies previously unaddressed limiting factors in
76 carbon sink growth and nutrient removal, which can be used to develop more targeted policies aimed at reversing the
77 resulting negative impacts. Meanwhile, this study informs a new technology pathway for increasing carbon sinks and
78 mitigating seawater eutrophication, i.e. applying AU, which can broaden the spectrum of policy and management tools
79 to address climate change and marine pollution. Our findings also suggest that enhancing mariculture algae derived carbon
80 sinks and nutrient removal is a complex and systematic work that requires consideration of multiple influencing factors
81 and their positive and negative effects.



82

83 **Fig. 1.** General information of the study area. (a) The location of Shandong Province in China; (b) AU field trial location in Shandong
 84 Province (36°22' N, 120°50' E); and (c) mariculture algae area and structure in Shandong Province between 2010 and 2020.

85 **2. Methodology and data**

86 **2.1. Measurement of carbon sink and nutrient removal of mariculture algae**

87 Algae take up CO₂ and dissolved inorganic carbon through photosynthesis as algae grow and convert it into organic
 88 carbon (Smith, 1981; Gao and McKinley, 1994). A portion of the organic carbon is removed from seawater after
 89 harvesting, forming the carbon sink of the algal body. In addition, algae also release some particulate organic carbon
 90 (POC) and dissolved organic carbon (DOC) into seawater (Tyler and McGlathery, 2006; Tang et al., 2011; Watanabe et
 91 al., 2020; Weigel and Pfister, 2021). A portion of POC and DOC will deposit in the deep ocean and seabed under microbial
 92 action to form stable sediments (Jiao et al., 2010). This fraction of sediments that can be stored for long periods is a carbon
 93 sink (Krause-Jensen and Duarte, 2016; Pan et al., 2019; Gao et al., 2021).

94 We calculated the carbon sink of mariculture algae (TC , assuming a total of i species) by adding three components
 95 (Yang et al., 2022) i.e., the carbon sink of the algal body (C_i), the carbon sink formed by releasing POC (C_i^{POC}), and the
 96 carbon sink formed by releasing DOC (C_i^{DOC}):

97
$$TC = \sum_{i=1}^n (C_i + C_i^{POC} + C_i^{DOC}) \quad (1)$$

98 When measuring the carbon sink of mariculture algae:

99 $C_i = DW_i \times w_i^C$ (2)

100 $C_i^{\text{POC}} = C_i \times \frac{\alpha}{1-\alpha-\beta} \times r^{\text{POC}}$ (3)

101 $C_i^{\text{DOC}} = C_i \times \frac{\beta}{1-\alpha-\beta} \times r^{\text{DOC}}$ (4)

102 The carbon sink of the mariculture algal body (C_i) can be estimated from algal production (dry weight) (DW_i) and the
 103 carbon (C) content of algae (w_i^C). α and β represent the proportion of POC and DOC released during algal growth to
 104 algal photosynthetic productivity (Yan et al., 2011). r^{POC} and r^{DOC} are the proportion of POC and DOC released by
 105 algae that are eventually converted into carbon sinks.

106 N and P removal by algae was determined by algal production (dry weight) and the N and P content of algae. The
 107 specific calculation formula is as follows:

108 $N_i = DW_i \times w_i^N$ (5)

109 $P_i = DW_i \times w_i^P$ (6)

110 Here, N_i and P_i represent N and P removal, w_i^N and w_i^P are the N and P content of the algae.

111 **2.2. Driving force analysis using the Logarithmic Mean Divisia Index approach**

112 We used the Logarithmic Mean Divisia Index (LMDI) method to decompose changes in carbon sinks and nutrient
 113 removal by mariculture algae. Proposed by Ang et al. (2004), the LMDI method employs a logarithmic transformation,
 114 which is an applicable method to quantify the drivers of a given variable without any residual terms after decomposition.
 115 Compared to other decomposition methods, the results obtained from LMDI decomposition are intuitive and easy to
 116 interpret (Nzudie et al., 2021), making it a valuable tool in various fields, including carbon emissions (Ma et al., 2003),
 117 energy intensity (Wang et al., 2005), and water footprint (Zhao et al., 2017). We identified four driving factors i.e.,
 118 intensity, yield, structure, and area, as shown in Eq. 7:

119
$$M = \sum_{i=1}^n \frac{M_i}{DW_i} \times \frac{DW_i}{A_i} \times \frac{A_i}{A} \times A = \sum_{i=1}^n I_i \times Y_i \times S_i \times A$$
 (7)

120 Here, M represents the carbon sink or nutrient removal of mariculture algae; subscript i represents algal species i , and
 121 n represents the total number of algal species (for this study $n = 4$); DW_i represents the production of algal species i ;
 122 A_i is the mariculture area used for growth of algal species i ; A refers to the total mariculture area of algae. I , Y , S ,
 123 and A represent intensity, yield, structure, and area, respectively. Intensity is the amount of carbon sink or nutrient
 124 removal per unit of algal species i 's production. Yield describes the amount of production per unit of algal species i 's
 125 area. Structure is the ratio of algal species i 's area to the total area of all algae, representing the effect of algal species
 126 changes. Area reflects how the total area of mariculture algae can impact the carbon sink or nutrient removal of algal
 127 species i .

128 The total changes in the carbon sink or nutrient removal of mariculture algae can thus be formulated as:

129 $\Delta M = M^t - M^0 = \Delta I + \Delta Y + \Delta S + \Delta A$ (8)

130 where ΔI (intensity effect), ΔY (yield effect), ΔS (structure effect), and ΔA (area effect) are changing driving factors
 131 of ΔM .

132 The value of I_i depends on the C, N, and P content of algae, which varies in different mariculture areas and seasons.
 133 However, we do not consider the changes in these parameters in our measurement. Such setting is primarily because our
 134 focus was on studying the carbon sink of the algal body at the time of harvest. Changes in C, N and P content of algal
 135 body during the harvest season are relatively small (He et al. 2008; Xiao et al. 2017; Zhang et al. 2020). In the subsequent
 136 analysis, I_i remains unchanged and the contribution from the intensity effect (ΔI) to the increase in algae derived carbon
 137 sinks and nutrient removal amounts to 0.

138 According to the LMDI approach, the equations to decompose the changes to mariculture algae derived carbon sinks
 139 or nutrient removal are as follows:

140 $\Delta M_I = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{I_i^t}{I_i^0})]$ (9)

141 $\Delta M_Y = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{Y_i^t}{Y_i^0})]$ (10)

142 $\Delta M_S = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{S_i^t}{S_i^0})]$ (11)

143 $\Delta M_A = \sum_{i=1}^n [L(M_i^t, M_i^0) \times \ln(\frac{A_i^t}{A_i^0})]$ (12)

144 Where t and 0 represent the latter and former year during the change, respectively. L is the log-average function,
 145 which satisfies:

146 $L(M_i^t, M_i^0) = \frac{M_i^t - M_i^0}{\ln(M_i^t) - \ln(M_i^0)}, M_i^t \neq M_i^0$ (13)

147 $L(M_i^t, M_i^0) = M_i^t, M_i^t = M_i^0$ (14)

148 **2.3. Scenario setting**

149 To estimate the potential for AU to offset the limiting effects on algae derived carbon sinks and nutrient removal by
 150 2030, we set a No-AU scenario based on the development characteristics of previous mariculture area growth, as well as
 151 four scenarios that consider the application of AU. The LMDI analysis was intended to reveal the driving factors that
 152 slow down the carbon sink and nutrient removal growth between 2014 and 2020. Thus, we were interested in establishing
 153 whether applying AU can effectively mitigate these negative factors. In the AU application scenarios, we intended to
 154 calculate the minimum percentage of areas where AU application can compensate for reducing carbon sinks (nutrient
 155 removal). We assumed that the yield of mariculture algae can increase by a factor of μ when applying AU. Our study
 156 aimed to determine the minimum AU application proportions required to achieve a comparable scale of carbon sink

157 (nutrient removal) as in the No-AU scenario by 2030 in the four AU application scenarios, namely λ_1 (scenario S1), λ_2
158 (scenario S2), λ_3 (scenario S3), and λ_4 (scenario S4). Between 2021 and 2030, AU would be applied annually in $\lambda/10$
159 of the mariculture area. The yield of mariculture algae in Shandong Province in 2030 would be $Y_{2020}(1 + \lambda \cdot \mu)$. The
160 details of the scenarios were as follows:

161 **No-AU scenario (N1).** In the No-AU scenario, the average annual change rates of the algal area between 2021 and
162 2030 remained consistent with the average change rates of the area between 2010 and 2020. The algal structure and yield
163 remain unchanged at 2020 levels.

164 **Area constant scenario (S1).** We assumed the mariculture area of algae remained at 2020 levels. The structure of algal
165 species would be the same as for the No-AU scenario. By 2030, the algal yield would be $Y_{2020}(1 + \lambda_1 \cdot \mu)$.

166 **Area reduction scenario (S2).** There has been a noticeable decline in the mariculture area in Shandong Province since
167 2017. Hence, this scenario assumed that future changes in the mariculture area would maintain this trend. Specifically,
168 the mariculture area continued to decrease between 2021 and 2030 at an average change rate to that observed between
169 2017 and 2020, while the algal structure would remain unchanged based on 2020 levels. By 2030, the algal yield would
170 be $Y_{2020}(1 + \lambda_2 \cdot \mu)$.

171 **Laver increase scenario (S3).** The contribution of algae to carbon sinks and mitigation of seawater eutrophication
172 varies with algal species (Zheng et al., 2019). The increase in the area proportion of laver will have a negative impact on
173 the growth of carbon sinks (nutrient removal). We therefore assumed that the area proportion of laver would continue to
174 increase by 2030, at a mean growth rate to that observed between 2010 and 2020, while the mariculture area was the same
175 as in the No-AU scenario. By 2030, algal yield would therefore be $Y_{2020}(1 + \lambda_3 \cdot \mu)$.

176 **Area reduction and laver increase scenario (S4).** The area given over to mariculture algal growth would be consistent
177 with scenario S2, and the algal structure would be consistent with scenario S3. We would also calculate the minimum
178 application ratio λ_4 of AU in order to achieve a comparable scale of carbon sink (nutrient removal) as in the No-AU
179 scenario.

180 **2.4. Uncertainty and sensitivity test**

181 In this study, we utilized a Monte Carlo simulation to estimate the uncertainties in carbon sink and nutrient removal of
182 mariculture algae. The overall uncertainty is calculated under the 95% confidence interval around the arithmetic mean.
183 The distribution characteristics of specific model parameters are shown in Table A1. Additionally, we performed a
184 sensitivity test for the carbon sink and nutrient removal of mariculture algae to analyse the impact of different input
185 parameters on the model outputs.

186 **2.5. Data collection**

187 We obtained data on the production and area of mariculture algae from the "Shandong Fishery Statistical Yearbook"
 188 (SFSY, 2011-2021). The specific biological parameters are shown in Table 1. The main mariculture algal species in
 189 Shandong Province were kelp, laver, and wakame, which together contributed approximately 90% of total production.
 190 Therefore, in the following study, the mariculture algae in Shandong Province were divided into four categories i.e., kelp,
 191 laver, wakame, and others.

Table 1
 Biological parameters of mariculture algae (%).

Species	Carbon content of algae (w_i^C)	Nitrogen content of algae (w_i^N)	Phosphorus content of algae (w_i^P)
Kelp	24.99	3.71	0.52
Laver	29.09	6.30	1.00
Wakame	30.48	5.01	0.76
Other algae	28.19	5.01	0.76

Notes: The C content ratio of kelp, laver, and wakame refer to Zhang et al. (2020). The C content of other algae species were taken as the mean values of kelp, laver, and wakame. The N and P content of kelp refer to Xiao et al. (2017). The N and P content of laver refer to He et al. (2008). Other algal species' N and P contents were taken as the mean values of kelp and laver.

192 Other parameters are shown in Table 2. We extract the parameters related to carbon sink formation from field studies
 193 and experimental data available in the literature. Consistent with the study by Yan et al. (2011), we adopt the values of
 194 α and β as 0.19 and 0.05, respectively (Khailov and Burlakova, 1969; Penhale and Capone, 1981; Yoshikawa et al.,
 195 2001). While previous studies have considered the carbon sink formed by releasing POC and DOC (Yan et al., 2011;
 196 Yang et al., 2022), field investigations have revealed that not all POC and DOC deposited on the seafloor contribute to
 197 carbon sink formation (Nelson et al., 2002; Jiao et al., 2010; Baetge et al., 2020). Nilsson et al. (2018) demonstrated that
 198 only 4% of the POC in the Baltic Sea was deposited on the seafloor to form carbon sinks. Chen et al. (2020) found that
 199 only 1.6% of the DOC released by algae remained unaltered by microorganisms and stably persisted in seawater. Hence,
 200 we assign the values of 0.04 and 0.016 to the parameters r^{POC} and r^{DOC} , respectively.

201

Table 2

The mechanism parameters of carbon sink of mariculture algae.

Mechanism parameters	Values	References
α	0.19	Yoshikawa et al. (2001); Yan et al. (2011)
β	0.05	Penhale and Capone (1981); Yan et al. (2011)
r^{POC}	0.04	Nilsson et al. (2018); Nelson et al. (2002)
r^{DOC}	0.016	Jiao et al. (2010); Chen et al. (2020)

202 The value of the average promotion rate on yield of AU (μ) was based on previous field experiments. Fan et al. (2019)
 203 compared 60 strains of algae from the distribution area of the AU system and an area remote from the AU system. They
 204 found that AU increased the average weight per algae by approximately 109.9%. Lin et al. (2019) found that the average
 205 weight of algae in the experimental group grown around the AU area was 33.1g, while the average weight of algae in the
 206 control group grown in the natural environment was 10.1g. Based on the above findings, we took a μ of 1.1 to ensure the
 207 reliability of the prediction results.

208 3. Results

209 3.1. Carbon sink and nutrient removal of mariculture algae between 2010 and 2020

210 Between 2010 and 2020, the average annual carbon sink of mariculture algae in Shandong Province was 162.20 kt,
 211 representing 23.14% of the carbon emissions of marine fisheries in 2014 (Yue et al., 2016). The carbon sink in the algal
 212 body accounted for 98.91% of the total mariculture algae derived carbon sinks, while the carbon sink formed via releasing
 213 POC and DOC contributed only 1.09%. The proportion of carbon sinks formed by POC and DOC measured in this study
 214 was lower than in other studies due to the lower r^{POC} and r^{DOC} values utilised (Yan et al., 2011; Yang et al., 2022).

215 The carbon sink of mariculture algae in Shandong Province showed an increasing trend between 2010 and 2020 (Table
 216 3), with an overall rate of 28.76%. The changes in carbon sinks may be divided into two distinct periods: from 2010 to
 217 2014, the average annual growth rate of mariculture algae derived carbon sink was 5.98%. While the average annual
 218 growth rate between 2014 and 2020 was only 0.34%.

219 The N and P removal trends are similar to those observed for carbon sinks. Specifically, between 2010 and 2014, there
 220 was a significant increase in N and P removal, with a rise of 26.78% and 27.49%, respectively. In contrast, the nutrient
 221 removal by mariculture algae was relatively stable between 2014 and 2020, with a modest increase of only 4.12% and
 222 4.85%, respectively.

223

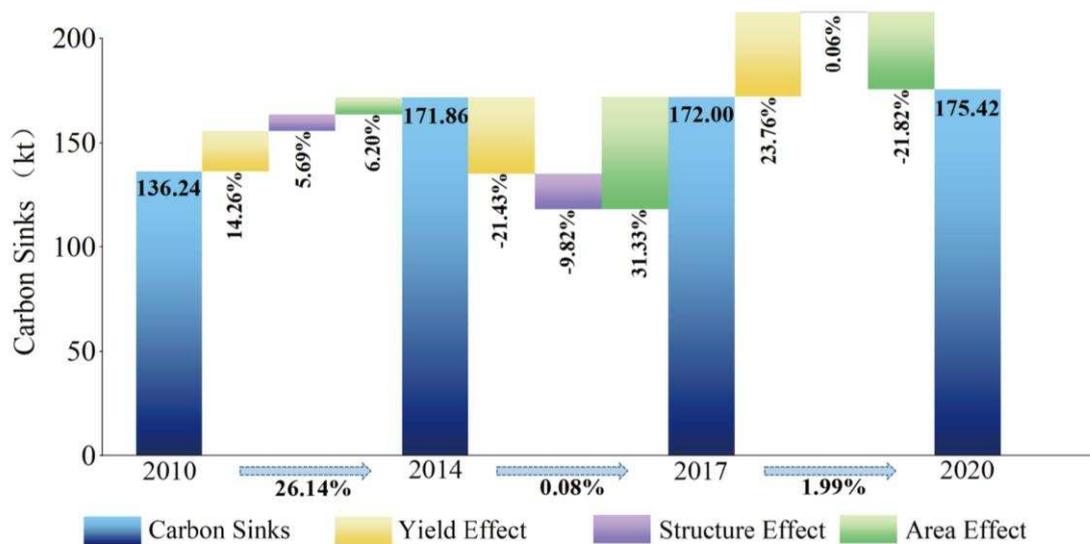
Table 3
The carbon sink and nutrient removal of mariculture grown algae in Shandong Province (kt).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Carbon sinks of algae body	134.75	129.58	145.69	151.04	169.98	170.75	173.67	170.12	172.81	172.76	173.51
Carbon sinks through POC	1.35	1.30	1.46	1.51	1.70	1.71	1.74	1.70	1.73	1.73	1.74
Carbon sinks through DOC	0.14	0.14	0.15	0.16	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Carbon sinks	136.24	131.01	147.30	152.71	171.86	172.64	175.59	172.00	174.72	174.67	175.42
Nitrogen Removal	20.50	19.76	22.28	23.09	25.99	26.12	26.79	26.31	26.94	27.18	27.06
Phosphorus Removal	2.91	2.81	3.18	3.29	3.71	3.73	3.84	3.77	3.88	3.93	3.89

224 **3.2. Driving force analysis for carbon sink and nutrient removal of mariculture algae**

225 We explored the driving factors (yield, structure, and area) leading to changes in carbon sink and nutrient removal of
 226 mariculture algae during the study period (Fig. 2). The analysis was divided into three periods: 2010-2014, 2014-2017,
 227 and 2017-2020. This division was based on the differences observed in the growth rates of carbon sinks and nutrient
 228 removal around 2014, as well as the clear downward trend in mariculture area used for algal growth since 2017.

229 Between 2010 and 2014 all three factors, i.e., yield, structure, and area, contributed to a rise in carbon sinks, resulting
 230 in a 26.14% increase in the carbon sink of algae relative to 2010. The yield effect stood out as the primary cause for
 231 increased carbon sinks (contributing 14.26% of the increase). Between 2014 and 2017, carbon sinks only increased by
 232 0.08% based on the 2014 level, and the effect of area became the major contributor to increased carbon sinks (53.84 kt,
 233 31.33%). In contrast, yield and structure showed inhibitory effects, resulting in a 21.43% and 9.82% reduction in carbon
 234 sinks, respectively. Between 2017 and 2020, the yield effect (40.87 kt, 23.76%) contributed positively to carbon sink
 235 growth, which was mostly offset by the negative effects of area (37.53 kt, 21.82%), resulting in only a slight increase in
 236 algae derived carbon sinks (1.99%). Meanwhile, the structure effect had little impact on carbon sinks (0.10 kt, 0.06%).
 237 The driving factors for N and P removal from mariculture algae in Shandong Province were similar to those found for
 238 carbon sinks (Fig. S1).



239

240 **Fig. 2.** Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt). The intensity effect
 241 (ΔI) is set to 0 and not shown in the figure.

242 We found driving force effects coincided with changes to the marine environment and policy adjustments. Prior to
 243 2014, production, area, and yield of mariculture algae in Shandong Province grew rapidly, encouraged by policies such
 244 as increased investment in marine fishery fixed assets, subsidising of fisheries diesel, and supporting fisheries resources
 245 protection (Liang et al., 2018; Han and Jiang, 2019). At the end of 2016, China released the 13th Five-Year Plan of
 246 National Fishery Development, which emphasized the implementation of coastal ecological protection and promoted
 247 structural reform on the supply side of fisheries (Cao et al., 2017; Su et al., 2021). As a result, many policies began to
 248 restrict the expansion of mariculture areas. For example, the Blue Bay Remediation Project (BBRP) was one of the major
 249 marine projects in China's 13th Five-Year Plan for ecological environmental protection, with Rizhao, Yantai, Weihai, and
 250 Qingdao in Shandong Province being selected as participating cities in early 2017. The project restricted or banned certain
 251 aquaculture activities in near-shore waters and targeted algal rafts for cleanup (Liu et al., 2019; Wang et al., 2020). In
 252 addition, several ecological policies, such as the "returning ponds to natural wetlands", have been implemented in some
 253 coastal aquaculture regions, leading to a significant decline in the mariculture algae area (Wang et al., 2023).

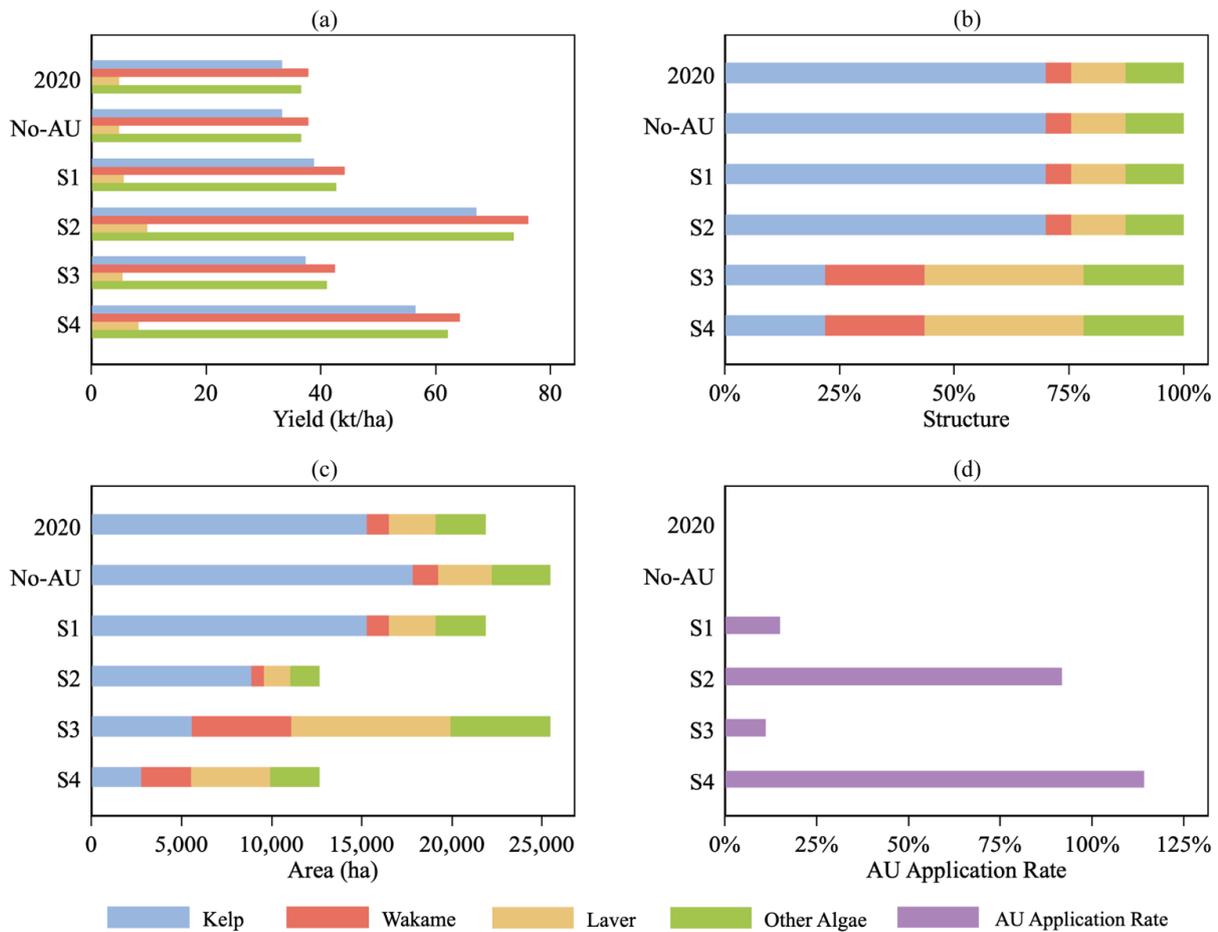
254 The yield effect showed a fluctuant trend between 2010 and 2020. This might be because artificial inputs and immature
 255 mariculture techniques dominated algae farming, which makes algal yield susceptible to extreme natural disasters,
 256 environmental conditions, water quality, and diseases (Zhang and Han, 2017).

257 The negative structural effect was primarily attributed to the increased share of laver in the mariculture area, as the
 258 carbon sink and nutrient removal per unit area of laver were less than 1/5 that of kelp and wakame. The share of laver
 259 increased from 1.34% to 11.80% during 2014-2020. The growing market demand for laver, a nutritious and healthy food
 260 (Brown et al., 2014), is causing the area of laver to expand. Meanwhile, rising seawater temperatures due to global

261 warming have led to disease outbreaks in Jiangsu Province, China's primary laver producing area, which led to many
 262 mariculture companies turning to promote the cultivation and demonstration of the laver in Shandong Province (Lu et al.,
 263 2022).

264 **3.3. Scenario analysis of the potential of AU for algae derived carbon sink and eutrophication mitigation**

265 We conducted a scenario analysis to evaluate the extent to which AU can offset the effects of two negative factors i.e.,
 266 area reduction and a more laver-oriented mariculture algal system. Fig. 3 shows the required application ratio of AU and
 267 the algal yield, structure, and area in 2030 to achieve the same carbon sink level as the No-AU scenario under different
 268 scenarios.



269 **Fig. 3.** Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030. The No-AU Scenario (No-AU) represents
 270 the case in which the mariculture algal area will grow at an average growth rate between 2010 and 2020, with structure and yield
 271 remaining unchanged from 2020 levels. Scenarios 1-4 (S1-S4) represent constant area scenarios, area reduction scenarios, increased
 272 laver scenario, and area reduction and laver increase scenarios, respectively.
 273

274 In the No-AU scenario, the algal area will continue to increase at an average annual growth rate between 2010 and
 275 2020, with the structure remaining consistent with the 2020 level. When no AU technology is applied, the carbon sink of

276 mariculture algae in Shandong Province will reach 204.41 kt by 2030, with corresponding N and P removal of 31.53 kt
277 and 4.54 kt, respectively.

278 Applying AU may compensate for the loss of carbon sink due to diminishing mariculture area and laver-oriented
279 structural change. In scenario S1, where the mariculture area and structure of algae remain unchanged at 2020 levels,
280 applying AU to 15.02% of the mariculture area was sufficient to achieve the same carbon sink level as in the No-AU
281 scenario by 2030. However, when the mariculture area decreases at the same rate as observed between 2017 and 2020
282 (scenario S2), AU would need to be applied to 91.81% of the area. In scenario S3, we assumed that the mariculture algal
283 area would maintain the same growth as for the No-AU scenario, while the proportion of laver would grow to 34.53% by
284 2030. In this case, applying an AU to 11.14% of the mariculture algal area would be necessary.

285 It is worth noting there is also a limit to the potential of AU to increase carbon sinks. AU will not fully compensate for
286 the negative effects of continuous mariculture area decline and the increase in the proportion of laver area (scenario S4).
287 We found that when AU was implemented across the entire mariculture area by 2030, it would compensate at most for a
288 carbon sink reduction of 44.52% in mariculture algal area compared to 2020, assuming algal structure remained constant.
289 Similarly, supposing the mariculture area was maintained at 2020 levels with 100% application of AU, the loss of carbon
290 sinks would not be compensated for when the share of laver exceeded 72.57%.

291 Applying AU can also compensate for the reduction in N and P removal due to mitigation in algal area and an increase
292 in the amount of laver (see Table A2). In the area reduction scenario (scenario S2), 96.23% and 95.46% of the area would
293 require AU application to secure identical N and P removal, respectively, as for the No-AU scenario by 2030. However,
294 the potential of AU would reach its limit when the area declined by more than 44.52% of the 2020 level. In the increased
295 laver scenario (scenario S3), where the laver area share increased to 34.53%, AU application rates would be 3.82% and
296 0.08% for N and P removal, respectively. If the share of laver exceeded 78.89% and 81.58%, achieving the same N and
297 P removal, respectively, as in the No-AU scenario then applying AU alone would no longer be feasible.

298 **4. Discussion**

299 ***4.1. Improving key factors that influence carbon sinks and nutrient removal***

300 China has acknowledged the importance of ocean carbon sinks, particularly algae derived carbon sinks, in mitigating
301 climate change (Yang et al., 2021). The country has laid out a policy system to support the development of ocean carbon
302 sinks around the goal of carbon peak and carbon neutrality. Despite the importance of algae for increasing carbon sinks
303 and achieving carbon neutrality, the incremental carbon sinks of algae have been limited in recent years (Gu and Yin,
304 2022; Wu and Li, 2022; Yang et al., 2022). In this study, we identified the main limiting factors of algae derived carbon
305 sinks and their contributions by proposing driving factors such as yield, structure, and area. Unlike the results of previous
306 studies (Shao et al., 2019; Ren, 2021; Yang et al., 2022), we demonstrated the importance of taking area into account as

307 a driving force. The results showed that area was the most critical factor driving the growth of algae derived carbon sinks
308 until 2017. However, between 2017 and 2020, decreasing area had a significant inhibitory effect on carbon sinks. Our
309 study also revealed the negative impacts of laver expansion and unstable yields on carbon sinks. The biased mariculture
310 algae structure of laver hindered the growth of carbon sinks, and yields that fluctuate significantly over time are less
311 conducive to the stable enhancement of carbon sinks. We found similar conclusions regarding influencing factors for N
312 and P removal. The findings have contributed to adjusting mariculture industry policies regarding improved area, structure,
313 and yield to support the growth of mariculture algae derived carbon sink and nutrient removal.

314 To guarantee a steady increase in algae derived carbon sinks and nutrient removal, we propose the application of AU
315 in mariculture areas. AU provides a new impetus to the growth of algae derived carbon sinks and nutrient removal by
316 increasing yield against the negative impacts of area constraint and changes in structure changes. Our research
317 investigated the potential for AU to offset these negative effects. The results showed that enhancing carbon sink and
318 nutrient removal through AU is feasible. However, the promotion of AU also faces challenges, including its low energy
319 efficiency and high installation costs (Fan et al., 2013; Viudez et al., 2016; Qiang et al., 2018). These challenges need to
320 be considered in successful implementation of AU technology and achievement of better results in Shandong Province
321 and other coastal areas. Using clean energy to achieve self-powered AU is crucial in application of AU (Pan et al., 2018),
322 and can effectively reduce energy consumption and greenhouse gas emissions. Specifically, offshore wind, solar and tidal
323 energy can be harnessed for in-situ power generation, while wave or ocean current energy can be utilized to drive
324 upwelling and further optimize energy efficiency. Meanwhile, AU may benefit from special subsidies, tax breaks, and
325 technology research support for blue carbon. Government and market instruments can be used to provide technical and
326 financial support for AU application and promotion.

327 The yield effect was unstable between 2010 and 2020, partially due to the dominance of immature mariculture
328 techniques that make algal yield susceptible to natural disasters, environmental conditions, and disease (Zhang and Han,
329 2017). Whether AU can solve or mitigate yield fluctuation problem remains unknown. To achieve an increased and steady
330 yield, AU could combine with other farming techniques, for example: (a) use of remote sensing technology and marine
331 monitoring technology to plan cultivation sites according to required environmental conditions for the growth of different
332 algal species (Ai et al., 2023); (b) developing integrated multi-trophic aquaculture (IMTA) and using interactions between
333 aquatic plants and animals at different trophic levels to improve mariculture efficiency (Cutajar et al., 2022; Hargrave et
334 al., 2022); and (c) genetic improvements, such as developing adaptable and disease-resistant algal cultivars (Hu et al.,
335 2021).

336 Notably, there is an upper limit to the benefits achieved through AU. Where mariculture area declines, or the proportion
337 of laver increases, applying AU may not achieve the desired carbon sink and nutrient removal levels. Currently,
338 mariculture grown algae in China is mainly associated with nearshore waters, and some mariculture areas have been

339 reduced or removed due to global climate change, seawater pollution, and policy requirements (Liu et al., 2019; Wang et
340 al., 2020). To solve this dilemma, focusing on pollution control and ecological restoration in the original nearshore
341 mariculture areas will help improve existing farming areas. In addition, offshore mariculture may be developed by
342 cultivating new species suitable for deep-water mariculture and developing new facilities to expand mariculture space.
343 We've also noticed farmers tend to prioritize economic value of algae over environmental function when selecting species
344 for cultivation (Zheng et al., 2019). Laver is more economically valuable and preferred by farmers, while kelp and wakame
345 have a higher carbon sink and nutrient removal rates per unit of farmed area (Ou et al., 2017). By establishing marine
346 carbon sink trading platforms, farmers can be encouraged and guided to grow more species with high carbon sinks to
347 convert algae with high carbon sink functions from resources to assets. As a result, market players who protect and restore
348 the ecological environment can receive reasonable returns.

349 **4.2. Limitations**

350 As with all studies of this nature there are some limitations to our work: (a) we have simplified the complexities of
351 market demand on mariculture algal production. Total algae production may not increase even with productivity-
352 enhancing techniques because the total demand may remain relatively constant; (b) AU works better for areas where
353 surface seawater is nutrient-poor (Fan et al., 2020). The percentage increase in acreage from AU (μ) may vary depending
354 on nutrient salt levels in different waters; (c) AU can increase carbon sink conversion efficiency by enhancing the
355 downward fluxes of POC (Baumann et al., 2021). We have not considered this effect in our projections of AU potential
356 due to a lack of robust and relevant parameters. The effect of AU may potentially increase the carbon sink formed by both
357 POC and DOC, providing an even more significant environmental benefit.

358 A point that needs to be emphasised is that as a geo-environmental project, applying AU may potentially have adverse
359 effects on the marine environment, particularly when implemented extensively in deep-sea areas (Ryan et al., 2009; Keller
360 et al., 2014; Kwiatkowski et al., 2015; Pan et al., 2016). However, in our scenario analysis, AU will be deployed in areas
361 designated for mariculture algae. Algae typically thrive in shallow coastal regions, and applying AU in these mariculture
362 algae areas away from the deep sea will not greatly impact the environment (Maruyama et al., 2004). Meanwhile, AU's
363 efficiency is also characterized by certain technical parameters, such as power demand (Pan et al., 2018). Using non-clean
364 energy-powered AU may partly offset its environmental benefits. Fortunately, recent field experiments have demonstrated
365 the feasibility of solar-powered AU (Fan et al., 2020). The energy efficiency of AU will continue to improve with the
366 development of energy management technology (Lin et al., 2019).

367 Our measurements of the carbon sink of mariculture algae were based on numerical models and parameters. In contrast
368 to previous studies (Yan et al., 2011; Ren, 2021; Yang et al., 2022), our measurement of carbon sink in algae considers
369 not only the carbon sink of the algal body but also POC and DOC, which allows us to capture the full extent of carbon

370 sequestration by the algae. In addition, the fact that only a small portion of POC and DOC contribute to the formation of
371 carbon sink is also considered (Nelson et al., 2002; Nilsson et al., 2018; Chen et al., 2020). We further analysed the
372 sensitivity of our results to the parameters r^{POC} , r^{DOC} , α , and β to test the robustness of our results. The detailed
373 results of the sensitivity test are shown in Table A3. The results showed that the carbon sink of mariculture algae will
374 increase by 0.018% to 0.129% in 2020 if the mechanism parameters were increased by 10%. We also estimated the
375 uncertainties of model parameters using Monte Carlo simulation methods. The uncertainty ranges of the carbon sink of
376 mariculture algae between 2010 and 2020 are presented in Fig. A.2. The uncertainty of carbon sinks (expressed as relative
377 standard deviation (RSD) that equals the standard deviation divided by the mean) ranged from 7.64% to 9.63%, indicating
378 that the results were reliable. However, the N and P removal uncertainties were relatively high, ranging from 21.31% to
379 26.56%, and 27.90% to 35.13%, respectively, which was due to the lack of precision and relatively large standard
380 deviation in the results of existing studies regarding the measurement of algal N and P content.

381 **5. Conclusions**

382 This study focused on exploring the potential of AU to enhance algae derived carbon sink and mitigate eutrophication
383 in the face of continued mariculture area degradation and undesired structural change. The limited growth of the
384 mariculture algae area in Shandong Province, China, and the more intensive cultivation of laver in the limited area has
385 resulted in minimal improvements in carbon sinks and nutrient removal levels since 2014. Our findings indicated that
386 applying AU could effectively compensate for the loss of carbon sink and nutrient removal caused by the decrease of
387 mariculture area or the increase of the laver share. Meanwhile, we observed that the potential for AU to achieve these
388 benefits has upper limits. It is worth mentioning that scenario analysis cannot calculate future carbon sinks and nutrient
389 removal accurately, but rather reflects a promising technical pathway for improving algae derived carbon sinks and
390 nutrient removal in the face of shrinking mariculture areas and suboptimal species selection. Further research could
391 investigate the implication of other potential variables, such as the intensity effect changes over time and AU energy
392 efficiency on the carbon sink and nutrient removal potential.

393 **CRedit authorship contribution statement**

394 **Chunlei Shen:** Conceptualization, Writing – original draft, Investigation, Formal analysis. **Xinya Hao:**
395 Conceptualization, Methodology, Software, Writing – review & editing. **Dong An:** Investigation, Data curation. **Martin**
396 **R. Tillotson:** Writing – original draft, Writing – review & editing. **Lin Yang:** Conceptualization, Supervision,
397 Investigation, Funding acquisition. **Xu Zhao:** Conceptualization, Writing – review & editing, Methodology, Funding
398 acquisition.

399 **Declaration of competing interest**

400 The authors declare that they have no known competing financial interests or personal relationships that could have
401 appeared to influence the work reported in this paper.

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Table 1
Biological parameters of mariculture algae (%).

Species	Carbon content of algae (w_i^C)	Nitrogen content of algae (w_i^N)	Phosphorus content of algae (w_i^P)
Kelp	24.99	3.71	0.52
Laver	29.09	6.30	1.00
Wakame	30.48	5.01	0.76
Other algae	28.19	5.01	0.76

Notes: The C content ratio of kelp, laver, and wakame refer to Zhang et al. (2020). The C content of other algae species were taken as the mean values of kelp, laver, and wakame. The N and P content of kelp refer to Xiao et al. (2017). The N and P content of laver refer to He et al. (2008). Other algal species' N and P contents were taken as the mean values of kelp and laver.

Table 2
The mechanism parameters of carbon sink of mariculture algae.

Mechanism parameters	Values	References
α	0.19	Yoshikawa et al. (2001); Yan et al. (2011)
β	0.05	Penhale and Capone (1981); Yan et al. (2011)
r^{POC}	0.04	Nilsson et al. (2018); Nelson et al. (2002)
r^{DOC}	0.016	Jiao et al. (2010); Chen et al. (2020)

Table 3

The carbon sink and nutrient removal of mariculture grown algae in Shandong Province (kt).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Carbon sinks of algae body	134.75	129.58	145.69	151.04	169.98	170.75	173.67	170.12	172.81	172.76	173.51
Carbon sinks through POC	1.35	1.30	1.46	1.51	1.70	1.71	1.74	1.70	1.73	1.73	1.74
Carbon sinks through DOC	0.14	0.14	0.15	0.16	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Carbon sinks	136.24	131.01	147.30	152.71	171.86	172.64	175.59	172.00	174.72	174.67	175.42
Nitrogen Removal	20.50	19.76	22.28	23.09	25.99	26.12	26.79	26.31	26.94	27.18	27.06
Phosphorus Removal	2.91	2.81	3.18	3.29	3.71	3.73	3.84	3.77	3.88	3.93	3.89

Fig. 1. General information of the study area.

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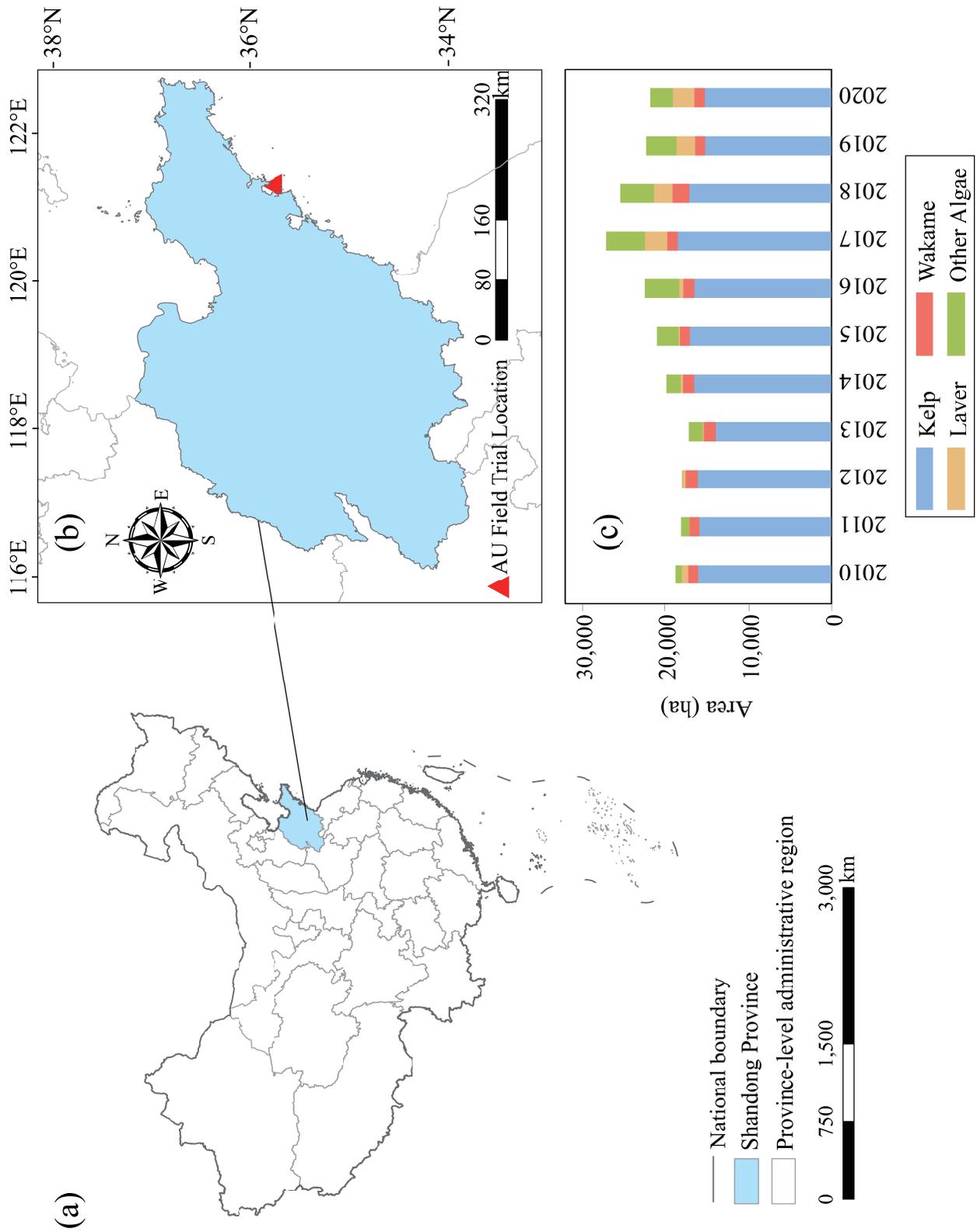


Fig. 2. Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt).

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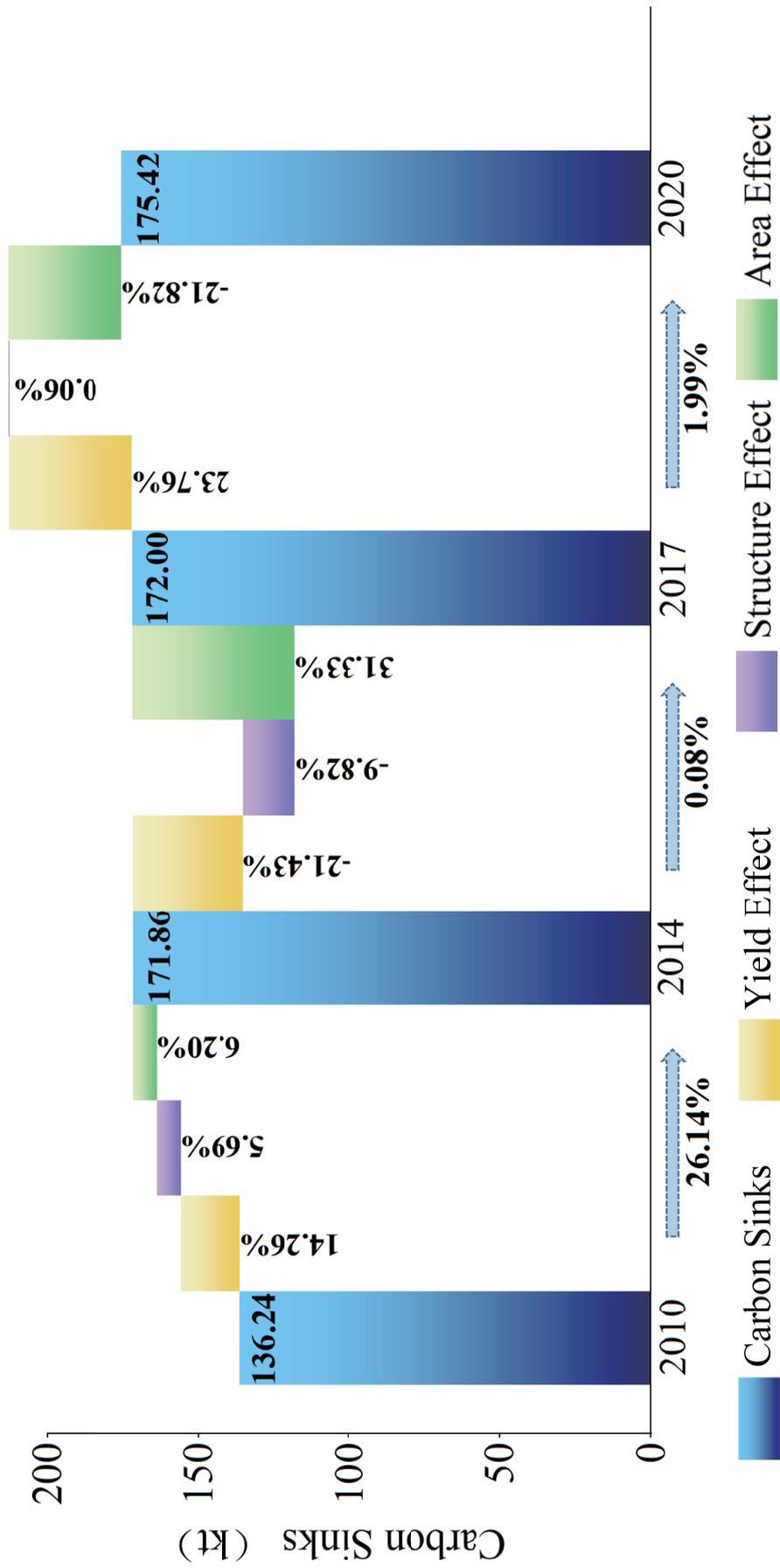


Fig. 3. Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030.

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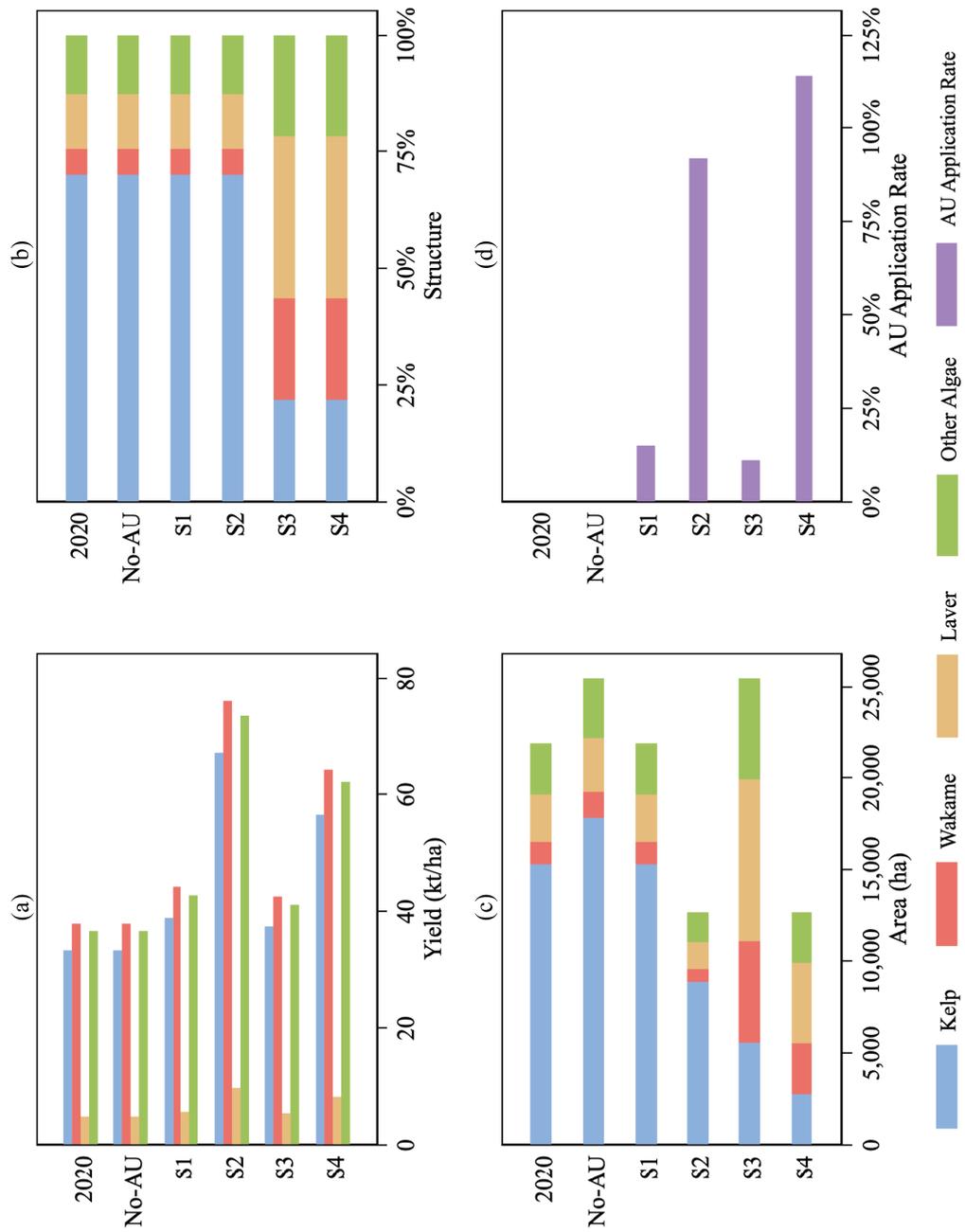


Fig. A1. Contribution of different driving factors to N and P removal changes in Shandong Province, China (2010-2020) (kt).

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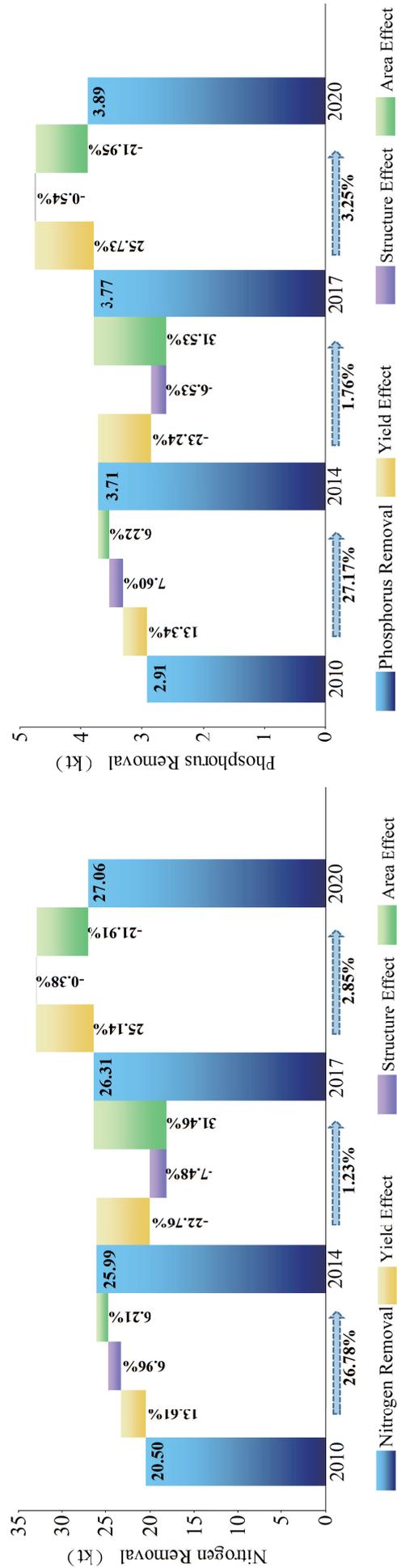
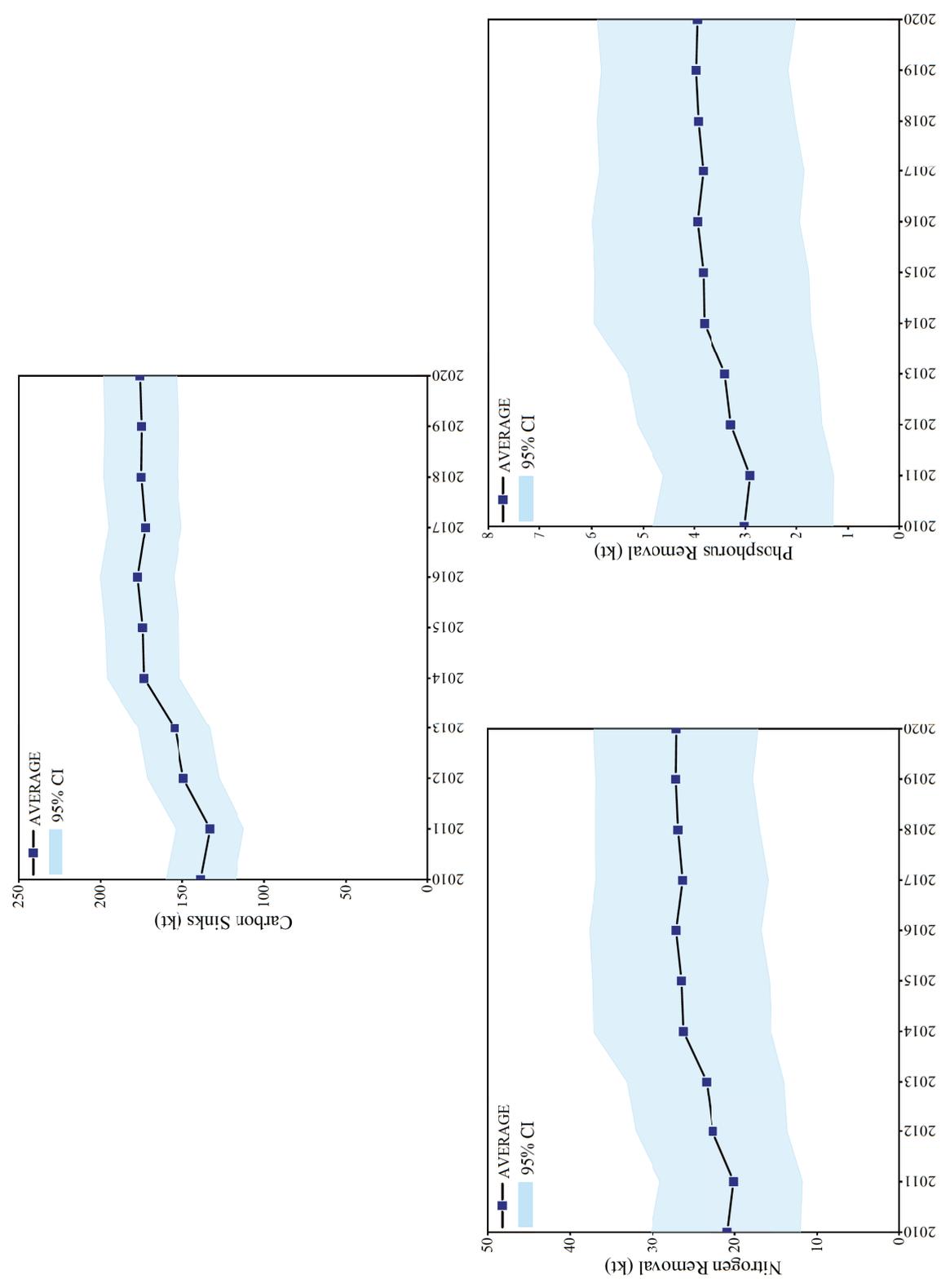


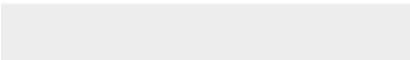
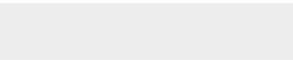
Fig. A2. Uncertainties in carbon sink and nutrient removal of mariculture algae between 2010 and 2020.

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Supplementary Material
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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contributions Statement

Chunlei Shen: Conceptualization, Writing – original draft, Investigation, Formal analysis. **Xinya Hao:** Conceptualization, Methodology, Software, Writing – review & editing. **Dong An:** Investigation, Data curation. **Martin R. Tillotson:** Writing – original draft, Writing – review & editing. **Lin Yang:** Conceptualization, Supervision, Investigation, Funding acquisition. **Xu Zhao:** Conceptualization, Writing – review & editing, Methodology, Funding acquisition.