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

Chunlei Shen[a], Xinya Hao[b], Dong An[a, c], Martin R. Tillotson[d], Lin Yang[a, *], Xu Zhao[e, *]

[a] *School of Business, Shandong University, Weihai 264209, China*

[b] *School of Energy and Environment, City University of Hong Kong, Hong Kong 999077, Hong Kong Special Administrative Region of China*

[c] *School of Bohai, Hebei Agricultural University, Baoding 071000, China*

[d] *School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK*

[e] *Institute of Blue and Green Development, Shandong University, Weihai 264209, China*

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.

* Corresponding authors.
E-mail addresses: yanglin2128@126.com (L. Yang), xuzhao@sdu.edu.cn (X. Zhao).

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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.

1. Introduction

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

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

Previous studies have addressed that the changes in production predominantly affect algae derived carbon sinks and nutrient removal. However, two key factors that influence changes in production, i.e. yield (production per area) and area, have been rarely studied. First, increasing the yield could offset the negative effects on algae production. One of the promising technics to enhance algae yield and subsequently increase algae derived carbon sinks is artificial upwelling (AU), which has been shown to increase mariculture algal yield in small-scale trials (Fan et al., 2019; Lin et al., 2019; Fan et al., 2020). AU is a system of mechanical equipment deployed in the mariculture area, which breaks the nutrient limitations of aquaculture by continuously upwelling the lower temperature, higher nutrient loaded seawater to the surface (Aure et al., 2007; Lovelock and Rapley, 2007; McClimans et al., 2010; Zollmann et al., 2019; Ortiz et al., 2022). AU in nutrient-rich waters can enhance the biological carbon pump in oligotrophic sea areas to sequester anthropogenic carbon dioxide (CO_2) and increase carbon sequestration (Oschlies et al.,2010; Pan et al., 2015; Gómez-Letona et al., 2022), and has been recognized by the United Nations Intergovernmental Panel on Climate Change (IPCC) as a global ocean carbon sink solution (IPCC, 2019). However, the potential of AU to offset the limitations on algae derived carbon sinks and nutrient removal remains unknown. Second, the reduction in mariculture area limits production growth, which inevitably affects the amount of algae derived carbon sinks and nutrient removal. However, no studies have yet been carried out to examine area as a driving factor to changes of carbon sinks and nutrient removal. Therefore, we further decompose mariculture production that predominantly affects algae derived carbon sinks and nutrient removal into two components i.e., yield and area. From this we hope to explore how algal yield may be enhanced through AU under limited expansion of mariculture area.

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

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

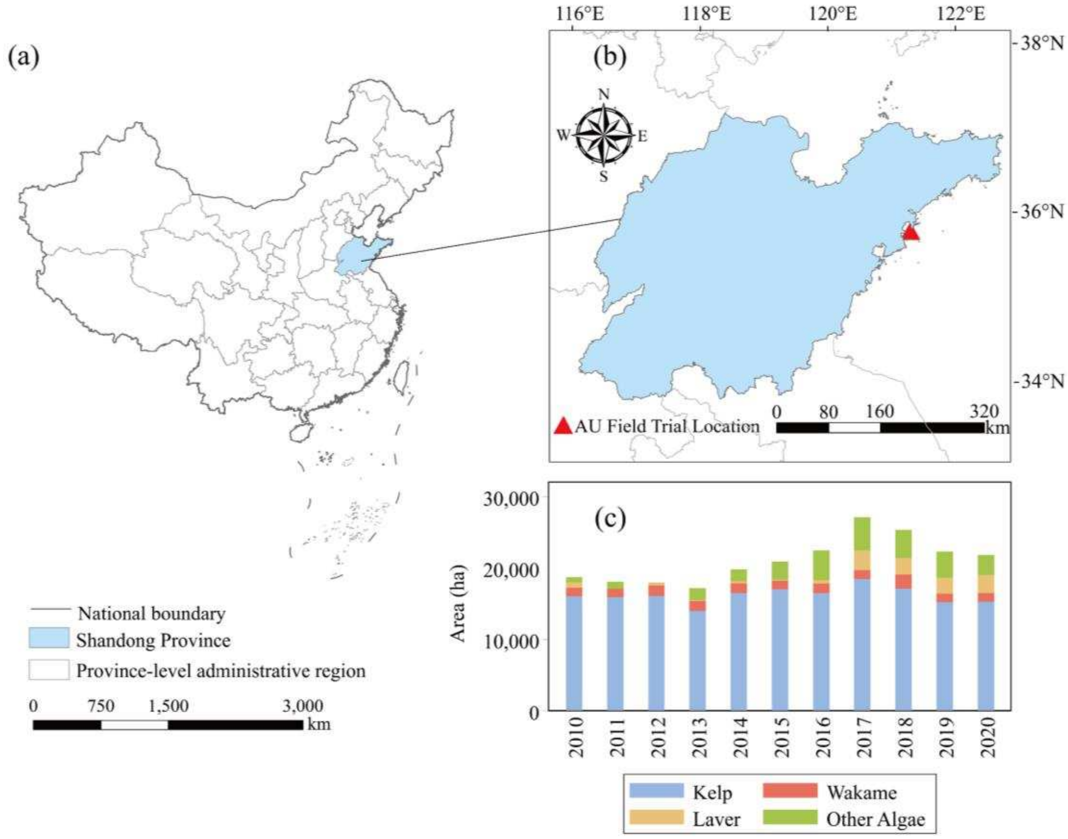

Fig. 1. General information of the study area. (a) The location of Shandong Province in China; (b) AU field trial location in Shandong Province (36˚22' N, 120˚50' E); and (c) mariculture algae area and structure in Shandong Province between 2010 and 2020.

2. Methodology and data

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

Algae take up CO_2 and dissolved inorganic carbon through photosynthesis as algae grow and convert it into organic carbon (Smith, 1981; Gao and McKinley, 1994). A portion of the organic carbon is removed from seawater after harvesting, forming the carbon sink of the algal body. In addition, algae also release some particulate organic carbon (POC) and dissolved organic carbon (DOC) into seawater (Tyler and McGlathery, 2006; Tang et al., 2011; Watanabe et al., 2020; Weigel and Pfister, 2021). A portion of POC and DOC will deposit in the deep ocean and seabed under microbial action to form stable sediments (Jiao et al., 2010). This fraction of sediments that can be stored for long periods is a carbon sink (Krause-Jensen and Duarte, 2016; Pan et al., 2019; Gao et al., 2021).

We calculated the carbon sink of mariculture algae (TC, assuming a total of i species) by adding three components (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 carbon sink formed by releasing DOC (C_i^{DOC}):

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

When measuring the carbon sink of mariculture algae：

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

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

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

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

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

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

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

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.

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

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

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

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

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

$$\Delta M = M^t - M^0 = \Delta I + \Delta Y + \Delta S + \Delta A \tag{8}$$

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

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

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

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

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

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

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

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

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

$$L(M_i^t, M_i^o) = M_i^t,\ M_i^t = M_i^o \tag{14}$$

2.3. Scenario setting

To estimate the potential for AU to offset the limiting effects on algae derived carbon sinks and nutrient removal by 2030, we set a No-AU scenario based on the development characteristics of previous mariculture area growth, as well as four scenarios that consider the application of AU. The LMDI analysis was intended to reveal the driving factors that slow down the carbon sink and nutrient removal growth between 2014 and 2020. Thus, we were interested in establishing whether applying AU can effectively mitigate these negative factors. In the AU application scenarios, we intended to calculate the minimum percentage of areas where AU application can compensate for reducing carbon sinks (nutrient removal). We assumed that the yield of mariculture algae can increase by a factor of μ when applying AU. Our study aimed to determine the minimum AU application proportions required to achieve a comparable scale of carbon sink (nutrient removal) as in the No-AU scenario by 2030 in the four AU application scenarios, namely λ_1 (scenario S1), λ_2 (scenario S2), λ_3 (scenario S3), and λ_4 (scenario S4). Between 2021 and 2030, AU would be applied annually in $\lambda/10$ of the mariculture area. The yield of mariculture algae in Shandong Province in 2030 would be $Y_{2020}(1 + \lambda \cdot \mu)$. The details of the scenarios were as follows:

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

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

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

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

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

2.4. Uncertainty and sensitivity test

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

2.5. Data collection

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

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

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)

The value of the average promotion rate on yield of AU (μ) was based on previous field experiments. Fan et al. (2019) compared 60 strains of algae from the distribution area of the AU system and an area remote from the AU system. They found that AU increased the average weight per algae by approximately 109.9%. Lin et al. (2019) found that the average weight of algae in the experimental group grown around the AU area was 33.1g, while the average weight of algae in the 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 reliability of the prediction results.

3. Results

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

Between 2010 and 2020, the average annual carbon sink of mariculture algae in Shandong Province was 162.20 kt, representing 23.14% of the carbon emissions of marine fisheries in 2014 (Yue et al., 2016). The carbon sink in the algal body accounted for 98.91% of the total mariculture algae derived carbon sinks, while the carbon sink formed via releasing POC and DOC contributed only 1.09%. The proportion of carbon sinks formed by POC and DOC measured in this study 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).

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

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

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

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

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

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

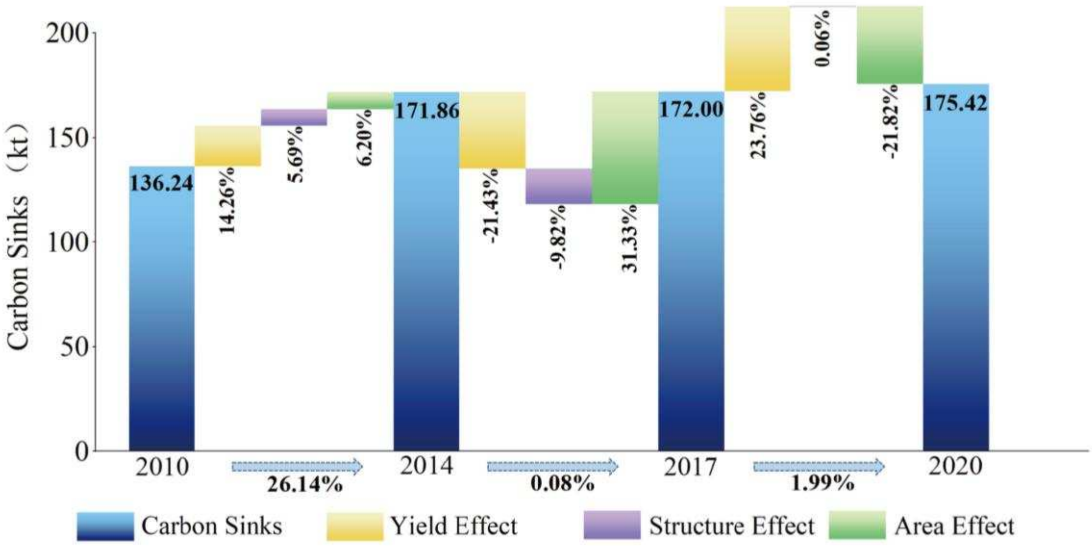

Fig. 2. Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt). The intensity effect (ΔI) is set to 0 and not shown in the figure.

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

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

The negative structural effect was primarily attributed to the increased share of laver in the mariculture area, as the carbon sink and nutrient removal per unit area of laver were less than 1/5 that of kelp and wakame. The share of laver increased from 1.34% to 11.80% during 2014-2020. The growing market demand for laver, a nutritious and healthy food (Brown et al., 2014), is causing the area of laver to expand. Meanwhile, rising seawater temperatures due to global warming have led to disease outbreaks in Jiangsu Province, China's primary laver producing area, which led to many mariculture companies turning to promote the cultivation and demonstration of the laver in Shandong Province (Lu et al., 2022).

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

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

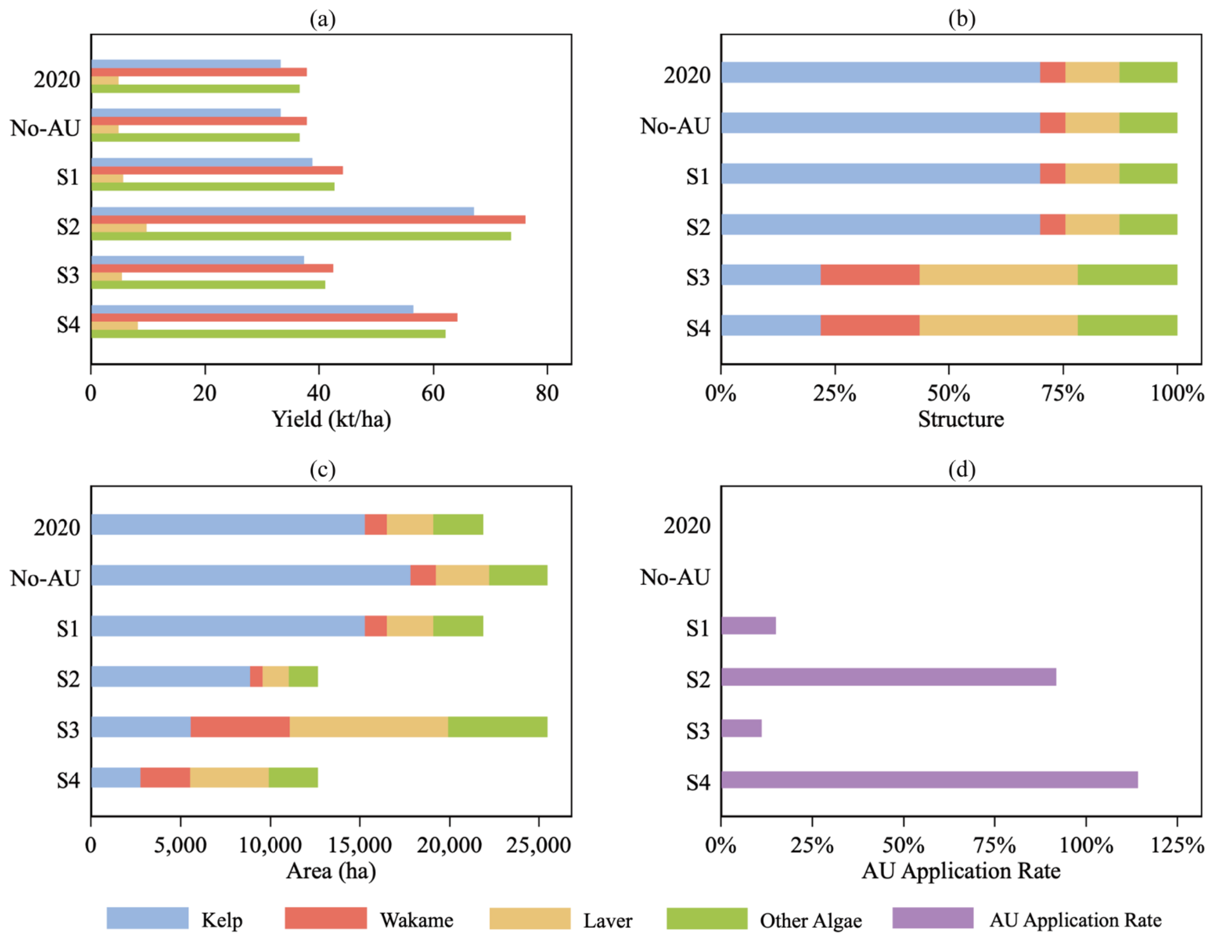

Fig. 3. Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030. The No-AU Scenario (No-AU) represents the case in which the mariculture algal area will grow at an average growth rate between 2010 and 2020, with structure and yield remaining unchanged from 2020 levels.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

In the No-AU scenario, the algal area will continue to increase at an average annual growth rate between 2010 and 2020, with the structure remaining consistent with the 2020 level. When no AU technology is applied, the carbon sink of mariculture algae in Shandong Province will reach 204.41 kt by 2030, with corresponding N and P removal of 31.53 kt and 4.54 kt, respectively.

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

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

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

4. Discussion

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

China has acknowledged the importance of ocean carbon sinks, particularly algae derived carbon sinks, in mitigating climate change (Yang et al., 2021). The country has laid out a policy system to support the development of ocean carbon sinks around the goal of carbon peak and carbon neutrality. Despite the importance of algae for increasing carbon sinks and achieving carbon neutrality, the incremental carbon sinks of algae have been limited in recent years (Gu and Yin, 2022; Wu and Li, 2022; Yang et al., 2022). In this study, we identified the main limiting factors of algae derived carbon sinks and their contributions by proposing driving factors such as yield, structure, and area. Unlike the results of previous studies (Shao et al., 2019; Ren, 2021; Yang et al., 2022), we demonstrated the importance of taking area into account as a driving force. The results showed that area was the most critical factor driving the growth of algae derived carbon sinks until 2017. However, between 2017 and 2020, decreasing area had a significant inhibitory effect on carbon sinks. Our study also revealed the negative impacts of laver expansion and unstable yields on carbon sinks. The biased mariculture algae structure of laver hindered the growth of carbon sinks, and yields that fluctuate significantly over time are less conducive to the stable enhancement of carbon sinks. We found similar conclusions regarding influencing factors for N and P removal. The findings have contributed to adjusting mariculture industry policies regarding improved area, structure, and yield to support the growth of mariculture algae derived carbon sink and nutrient removal.

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

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

Notably, there is an upper limit to the benefits achieved through AU. Where mariculture area declines, or the proportion of laver increases, applying AU may not achieve the desired carbon sink and nutrient removal levels. Currently, mariculture grown algae in China is mainly associated with nearshore waters, and some mariculture areas have been reduced or removed due to global climate change, seawater pollution, and policy requirements (Liu et al., 2019; Wang et al., 2020). To solve this dilemma, focusing on pollution control and ecological restoration in the original nearshore mariculture areas will help improve existing farming areas. In addition, offshore mariculture may be developed by cultivating new species suitable for deep-water mariculture and developing new facilities to expand mariculture space. We've also noticed farmers tend to prioritize economic value of algae over environmental function when selecting species for cultivation (Zheng et al., 2019). Laver is more economically valuable and preferred by farmers, while kelp and wakame have a higher carbon sink and nutrient removal rates per unit of farmed area (Ou et al., 2017). By establishing marine carbon sink trading platforms, farmers can be encouraged and guided to grow more species with high carbon sinks to convert algae with high carbon sink functions from resources to assets. As a result, market players who protect and restore the ecological environment can receive reasonable returns.

4.2. Limitations

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

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

Our measurements of the carbon sink of mariculture algae were based on numerical models and parameters. In contrast to previous studies (Yan et al., 2011; Ren, 2021; Yang et al., 2022), our measurement of carbon sink in algae considers not only the carbon sink of the algal body but also POC and DOC, which allows us to capture the full extent of carbon sequestration by the algae. In addition, the fact that only a small portion of POC and DOC contribute to the formation of carbon sink is also considered (Nelson et al., 2002; Nilsson et al., 2018; Chen et al., 2020). We further analysed the sensitivity of our results to the parameters r^{POC}, r^{DOC}, α, and β to test the robustness of our results. The detailed results of the sensitivity test are shown in Table A3. The results showed that the carbon sink of mariculture algae will increase by 0.018% to 0.129% in 2020 if the mechanism parameters were increased by 10%. We also estimated the uncertainties of model parameters using Monte Carlo simulation methods. The uncertainty ranges of the carbon sink of mariculture algae between 2010 and 2020 are presented in Fig. A.2. The uncertainty of carbon sinks (expressed as relative standard deviation (RSD) that equals the standard deviation divided by the mean) ranged from 7.64% to 9.63%, indicating that the results were reliable. However, the N and P removal uncertainties were relatively high, ranging from 21.31% to 26.56%, and 27.90% to 35.13%, respectively, which was due to the lack of precision and relatively large standard deviation in the results of existing studies regarding the measurement of algal N and P content.

5. Conclusions

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

CRediT authorship contribution 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.

Declaration of competing interest

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.

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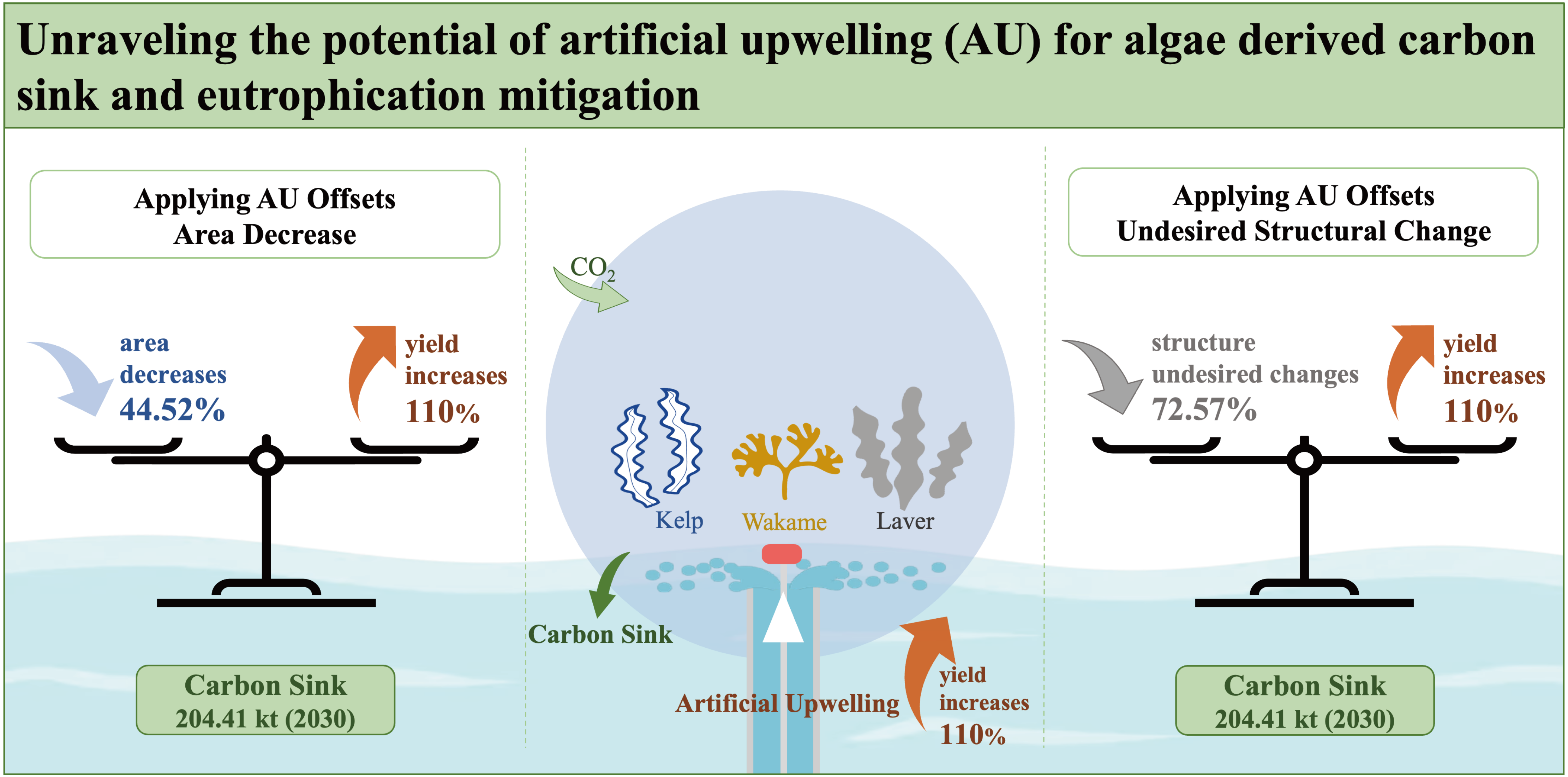
Graphical Abstract



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.

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

Chunlei Shen[a], Xinya Hao[b], Dong An[a,c], Martin R. Tillotson[d], Lin Yang[a,*], Xu Zhao[e,*]

[a] *School of Business, Shandong University, Weihai 264209, China*

[b] *School of Energy and Environment, City University of Hong Kong, Hong Kong 999077, Hong Kong Special Administrative Region of China*

[c] *School of Bohai, Hebei Agricultural University, Baoding 071000, China*

[d] *School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK*

[e] *Institute of Blue and Green Development, Shandong University, Weihai 264209, China*

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.

* Corresponding authors.
E-mail addresses: yanglin2128@126.com (L. Yang), xuzhao@sdu.edu.cn (X. Zhao).

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

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1. Introduction

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

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

Previous studies have addressed that the changes in production predominantly affect algae derived carbon sinks and nutrient removal. However, two key factors that influence changes in production, i.e. yield (production per area) and area, have been rarely studied. First, increasing the yield could offset the negative effects on algae production. One of the promising technics to enhance algae yield and subsequently increase algae derived carbon sinks is artificial upwelling (AU), which has been shown to increase mariculture algal yield in small-scale trials (Fan et al., 2019; Lin et al., 2019; Fan et al., 2020). AU is a system of mechanical equipment deployed in the mariculture area, which breaks the nutrient limitations of aquaculture by continuously upwelling the lower temperature, higher nutrient loaded seawater to the surface (Aure et al., 2007; Lovelock and Rapley, 2007; McClimans et al., 2010; Zollmann et al., 2019; Ortiz et al., 2022). AU in nutrient-rich waters can enhance the biological carbon pump in oligotrophic sea areas to sequester anthropogenic carbon dioxide (CO_2) and increase carbon sequestration (Oschlies et al.,2010; Pan et al., 2015; Gómez-Letona et al., 2022), and has been recognized by the United Nations Intergovernmental Panel on Climate Change (IPCC) as a global ocean carbon sink solution (IPCC, 2019). However, the potential of AU to offset the limitations on algae derived carbon sinks and nutrient removal remains unknown. Second, the reduction in mariculture area limits production growth, which inevitably affects the amount of algae derived carbon sinks and nutrient removal. However, no studies have yet been carried out to examine area as a driving factor to changes of carbon sinks and nutrient removal. Therefore, we further decompose mariculture production that predominantly affects algae derived carbon sinks and nutrient removal into two components i.e., yield and area. From this we hope to explore how algal yield may be enhanced through AU under limited expansion of mariculture area.

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

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

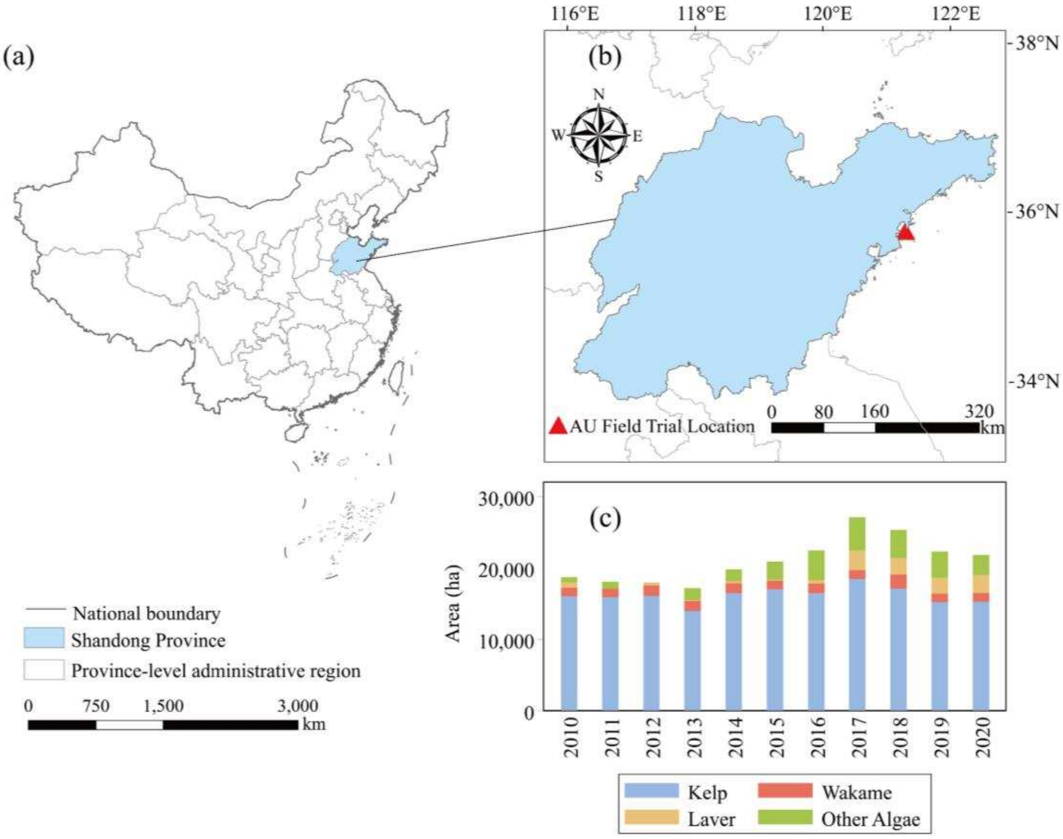

Fig. 1. General information of the study area. (a) The location of Shandong Province in China; (b) AU field trial location in Shandong Province (36˚22' N, 120˚50' E); and (c) mariculture algae area and structure in Shandong Province between 2010 and 2020.

2. Methodology and data

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

Algae take up CO_2 and dissolved inorganic carbon through photosynthesis as algae grow and convert it into organic carbon (Smith, 1981; Gao and McKinley, 1994). A portion of the organic carbon is removed from seawater after harvesting, forming the carbon sink of the algal body. In addition, algae also release some particulate organic carbon (POC) and dissolved organic carbon (DOC) into seawater (Tyler and McGlathery, 2006; Tang et al., 2011; Watanabe et al., 2020; Weigel and Pfister, 2021). A portion of POC and DOC will deposit in the deep ocean and seabed under microbial action to form stable sediments (Jiao et al., 2010). This fraction of sediments that can be stored for long periods is a carbon sink (Krause-Jensen and Duarte, 2016; Pan et al., 2019; Gao et al., 2021).

We calculated the carbon sink of mariculture algae (TC, assuming a total of i species) by adding three components (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 carbon sink formed by releasing DOC (C_i^{DOC}):

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

When measuring the carbon sink of mariculture algae：

$$C_i = DW_i \times w_i^C \tag{2}$$

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

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

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

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

$$N_i = DW_i \times w_i^N \tag{5}$$

$$P_i = DW_i \times w_i^P \tag{6}$$

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$L(M_i^t, M_i^o) = M_i^t,\ M_i^t = M_i^o \quad (14)$$

2.3. Scenario setting

To estimate the potential for AU to offset the limiting effects on algae derived carbon sinks and nutrient removal by 2030, we set a No-AU scenario based on the development characteristics of previous mariculture area growth, as well as four scenarios that consider the application of AU. The LMDI analysis was intended to reveal the driving factors that slow down the carbon sink and nutrient removal growth between 2014 and 2020. Thus, we were interested in establishing whether applying AU can effectively mitigate these negative factors. In the AU application scenarios, we intended to calculate the minimum percentage of areas where AU application can compensate for reducing carbon sinks (nutrient removal). We assumed that the yield of mariculture algae can increase by a factor of μ when applying AU. Our study aimed to determine the minimum AU application proportions required to achieve a comparable scale of carbon sink (nutrient removal) as in the No-AU scenario by 2030 in the four AU application scenarios, namely λ_1 (scenario S1), λ_2 (scenario S2), λ_3 (scenario S3), and λ_4 (scenario S4). Between 2021 and 2030, AU would be applied annually in $\lambda/10$ of the mariculture area. The yield of mariculture algae in Shandong Province in 2030 would be $Y_{2020}(1+\lambda\cdot\mu)$. The details of the scenarios were as follows:

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

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

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

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

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

2.4. Uncertainty and sensitivity test

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

2.5. Data collection

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

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

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)

The value of the average promotion rate on yield of AU (μ) was based on previous field experiments. Fan et al. (2019) compared 60 strains of algae from the distribution area of the AU system and an area remote from the AU system. They found that AU increased the average weight per algae by approximately 109.9%. Lin et al. (2019) found that the average weight of algae in the experimental group grown around the AU area was 33.1g, while the average weight of algae in the 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 reliability of the prediction results.

3. Results

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

Between 2010 and 2020, the average annual carbon sink of mariculture algae in Shandong Province was 162.20 kt, representing 23.14% of the carbon emissions of marine fisheries in 2014 (Yue et al., 2016). The carbon sink in the algal body accounted for 98.91% of the total mariculture algae derived carbon sinks, while the carbon sink formed via releasing POC and DOC contributed only 1.09%. The proportion of carbon sinks formed by POC and DOC measured in this study 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).

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

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

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

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

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

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

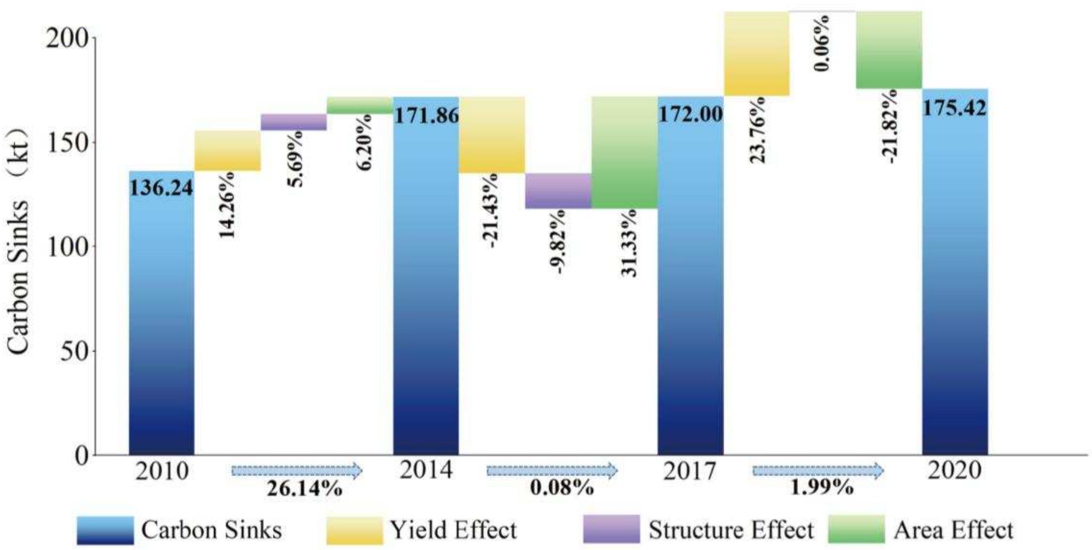

Fig. 2. Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt). The intensity effect (ΔI) is set to 0 and not shown in the figure.

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

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

The negative structural effect was primarily attributed to the increased share of laver in the mariculture area, as the carbon sink and nutrient removal per unit area of laver were less than 1/5 that of kelp and wakame. The share of laver increased from 1.34% to 11.80% during 2014-2020. The growing market demand for laver, a nutritious and healthy food (Brown et al., 2014), is causing the area of laver to expand. Meanwhile, rising seawater temperatures due to global warming have led to disease outbreaks in Jiangsu Province, China's primary laver producing area, which led to many mariculture companies turning to promote the cultivation and demonstration of the laver in Shandong Province (Lu et al., 2022).

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

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

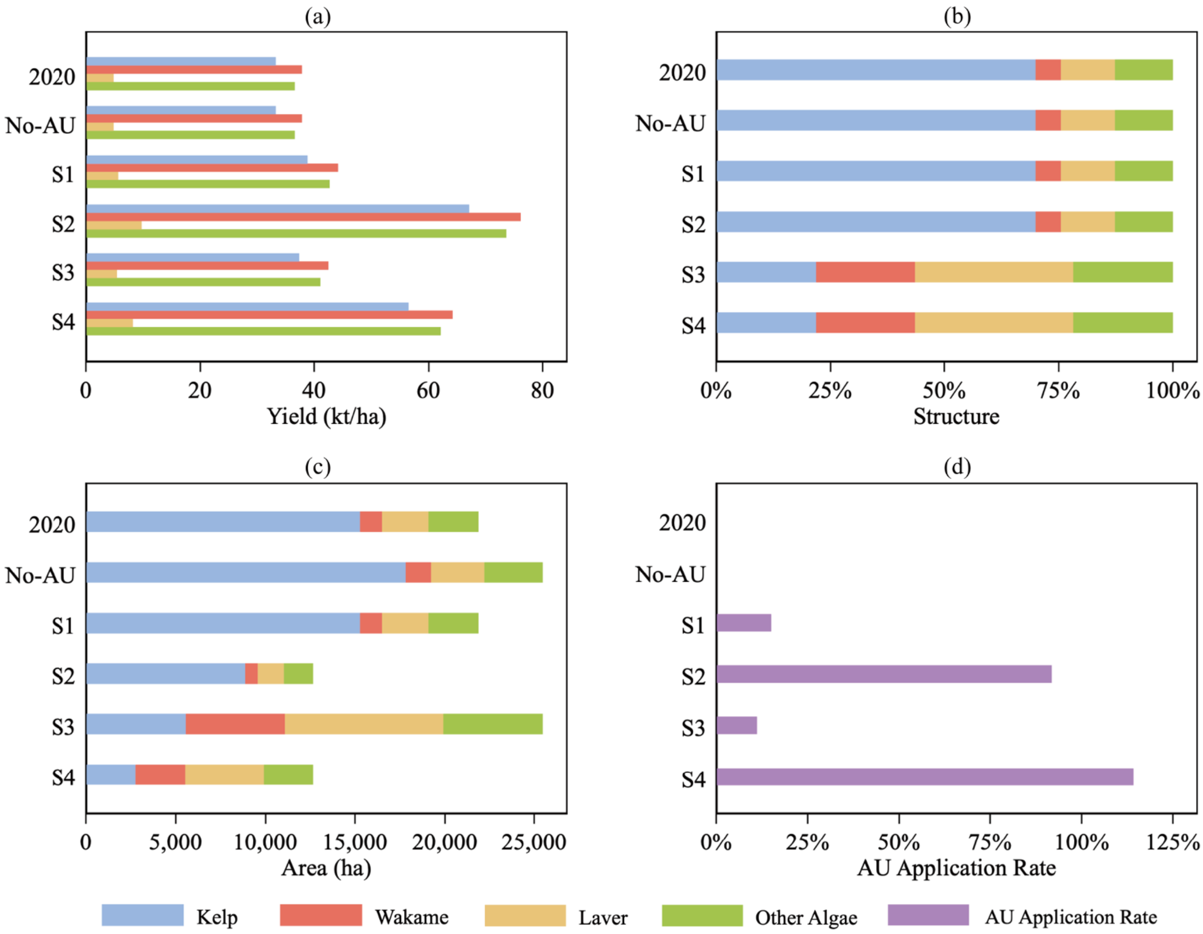

Fig. 3. Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030. The No-AU Scenario (No-AU) represents the case in which the mariculture algal area will grow at an average growth rate between 2010 and 2020, with structure and yield remaining unchanged from 2020 levels.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

In the No-AU scenario, the algal area will continue to increase at an average annual growth rate between 2010 and 2020, with the structure remaining consistent with the 2020 level. When no AU technology is applied, the carbon sink of mariculture algae in Shandong Province will reach 204.41 kt by 2030, with corresponding N and P removal of 31.53 kt and 4.54 kt, respectively.

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

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

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

4. Discussion

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

China has acknowledged the importance of ocean carbon sinks, particularly algae derived carbon sinks, in mitigating climate change (Yang et al., 2021). The country has laid out a policy system to support the development of ocean carbon sinks around the goal of carbon peak and carbon neutrality. Despite the importance of algae for increasing carbon sinks and achieving carbon neutrality, the incremental carbon sinks of algae have been limited in recent years (Gu and Yin, 2022; Wu and Li, 2022; Yang et al., 2022). In this study, we identified the main limiting factors of algae derived carbon sinks and their contributions by proposing driving factors such as yield, structure, and area. Unlike the results of previous studies (Shao et al., 2019; Ren, 2021; Yang et al., 2022), we demonstrated the importance of taking area into account as a driving force. The results showed that area was the most critical factor driving the growth of algae derived carbon sinks until 2017. However, between 2017 and 2020, decreasing area had a significant inhibitory effect on carbon sinks. Our study also revealed the negative impacts of laver expansion and unstable yields on carbon sinks. The biased mariculture algae structure of laver hindered the growth of carbon sinks, and yields that fluctuate significantly over time are less conducive to the stable enhancement of carbon sinks. We found similar conclusions regarding influencing factors for N and P removal. The findings have contributed to adjusting mariculture industry policies regarding improved area, structure, and yield to support the growth of mariculture algae derived carbon sink and nutrient removal.

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

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

Notably, there is an upper limit to the benefits achieved through AU. Where mariculture area declines, or the proportion of laver increases, applying AU may not achieve the desired carbon sink and nutrient removal levels. Currently, mariculture grown algae in China is mainly associated with nearshore waters, and some mariculture areas have been reduced or removed due to global climate change, seawater pollution, and policy requirements (Liu et al., 2019; Wang et al., 2020). To solve this dilemma, focusing on pollution control and ecological restoration in the original nearshore mariculture areas will help improve existing farming areas. In addition, offshore mariculture may be developed by cultivating new species suitable for deep-water mariculture and developing new facilities to expand mariculture space. We've also noticed farmers tend to prioritize economic value of algae over environmental function when selecting species for cultivation (Zheng et al., 2019). Laver is more economically valuable and preferred by farmers, while kelp and wakame have a higher carbon sink and nutrient removal rates per unit of farmed area (Ou et al., 2017). By establishing marine carbon sink trading platforms, farmers can be encouraged and guided to grow more species with high carbon sinks to convert algae with high carbon sink functions from resources to assets. As a result, market players who protect and restore the ecological environment can receive reasonable returns.

4.2. Limitations

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

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

Our measurements of the carbon sink of mariculture algae were based on numerical models and parameters. In contrast to previous studies (Yan et al., 2011; Ren, 2021; Yang et al., 2022), our measurement of carbon sink in algae considers not only the carbon sink of the algal body but also POC and DOC, which allows us to capture the full extent of carbon sequestration by the algae. In addition, the fact that only a small portion of POC and DOC contribute to the formation of carbon sink is also considered (Nelson et al., 2002; Nilsson et al., 2018; Chen et al., 2020). We further analysed the sensitivity of our results to the parameters r^{POC}, r^{DOC}, α, and β to test the robustness of our results. The detailed results of the sensitivity test are shown in Table A3. The results showed that the carbon sink of mariculture algae will increase by 0.018% to 0.129% in 2020 if the mechanism parameters were increased by 10%. We also estimated the uncertainties of model parameters using Monte Carlo simulation methods. The uncertainty ranges of the carbon sink of mariculture algae between 2010 and 2020 are presented in Fig. A.2. The uncertainty of carbon sinks (expressed as relative standard deviation (RSD) that equals the standard deviation divided by the mean) ranged from 7.64% to 9.63%, indicating that the results were reliable. However, the N and P removal uncertainties were relatively high, ranging from 21.31% to 26.56%, and 27.90% to 35.13%, respectively, which was due to the lack of precision and relatively large standard deviation in the results of existing studies regarding the measurement of algal N and P content.

5. Conclusions

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

CRediT authorship contribution 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.

Declaration of competing interest

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.

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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. Click here to access/download;Figure;Fig1.eps

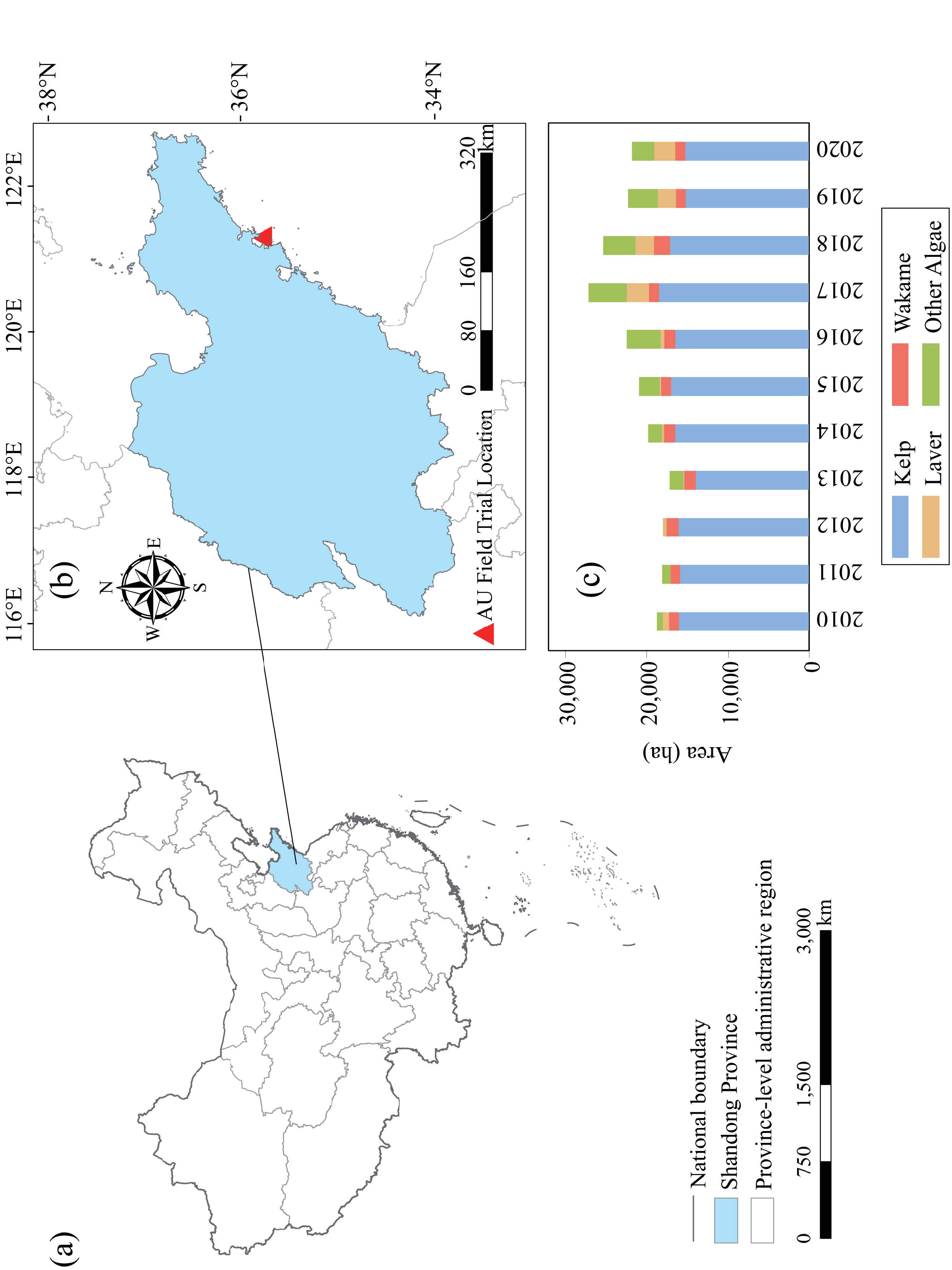

Fig. 2. Contribution of different driving factors to carbon sink changes in Shandong Province (2010-2020) (kt).

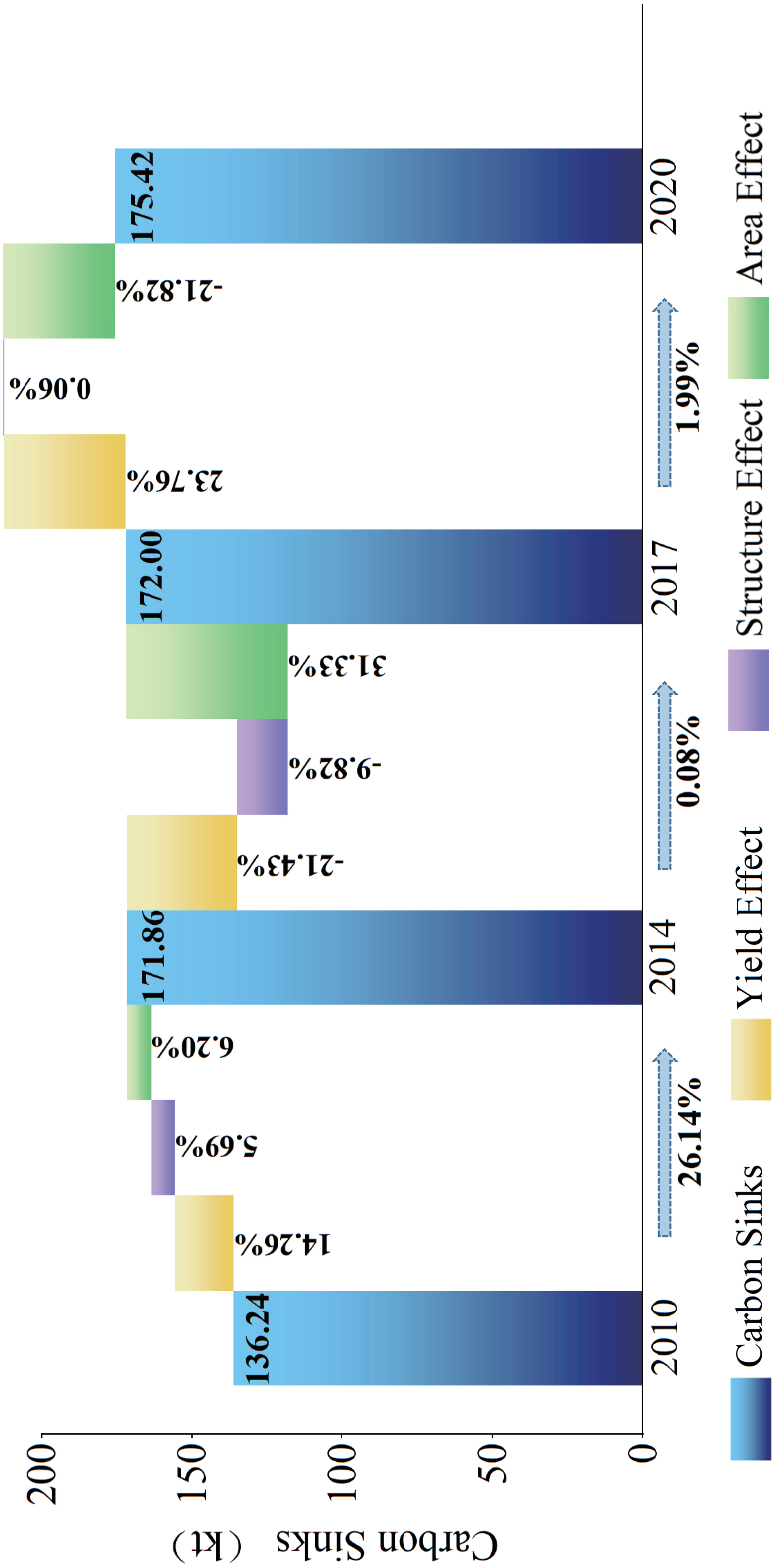

Fig. 3. Yield, structure, area, and AU application rates in 2020, and the five scenarios in 2030.

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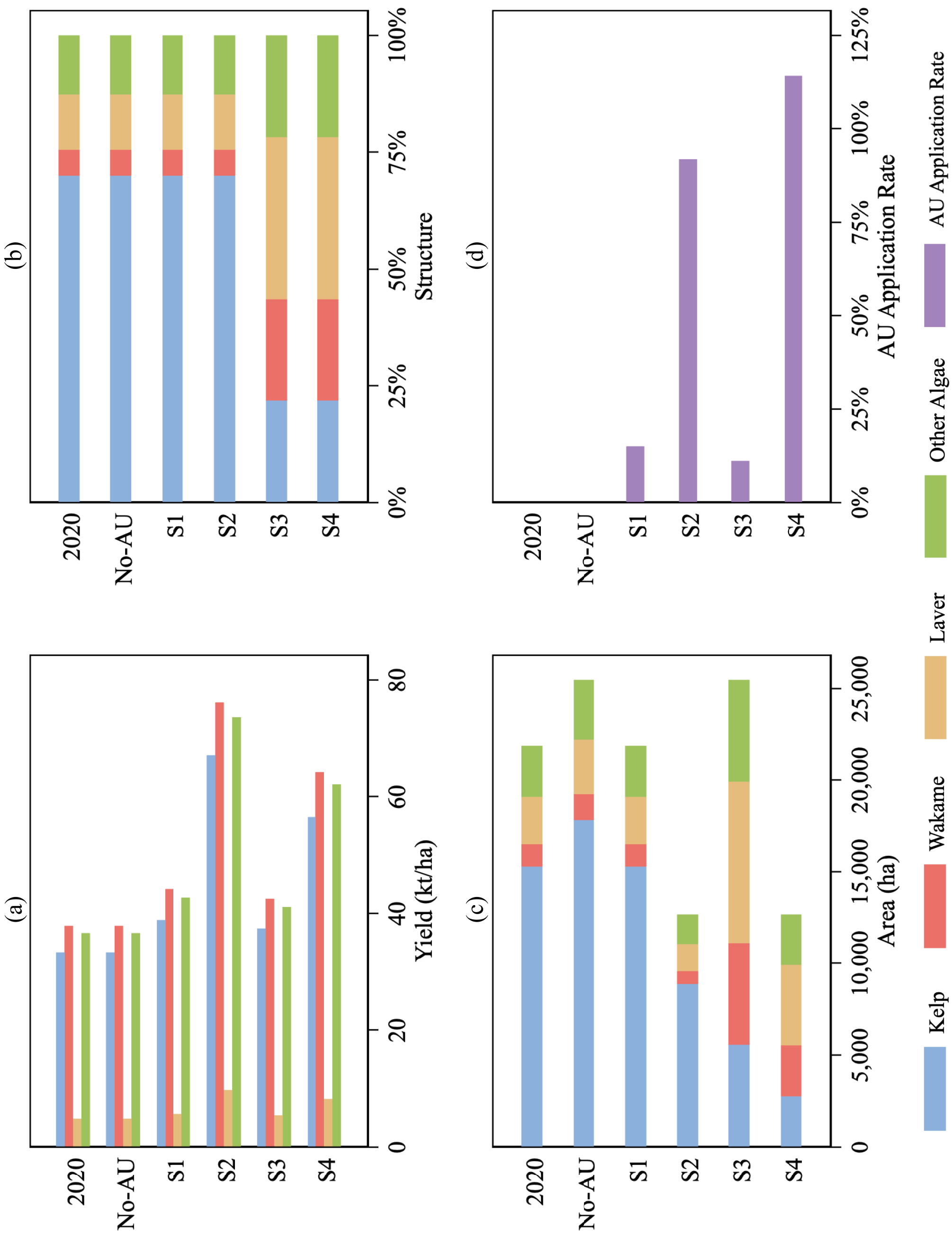

Fig. A1. Contribution of different driving factors to N and P removal changes in Shandong Province, China (2010-2020) (kt).

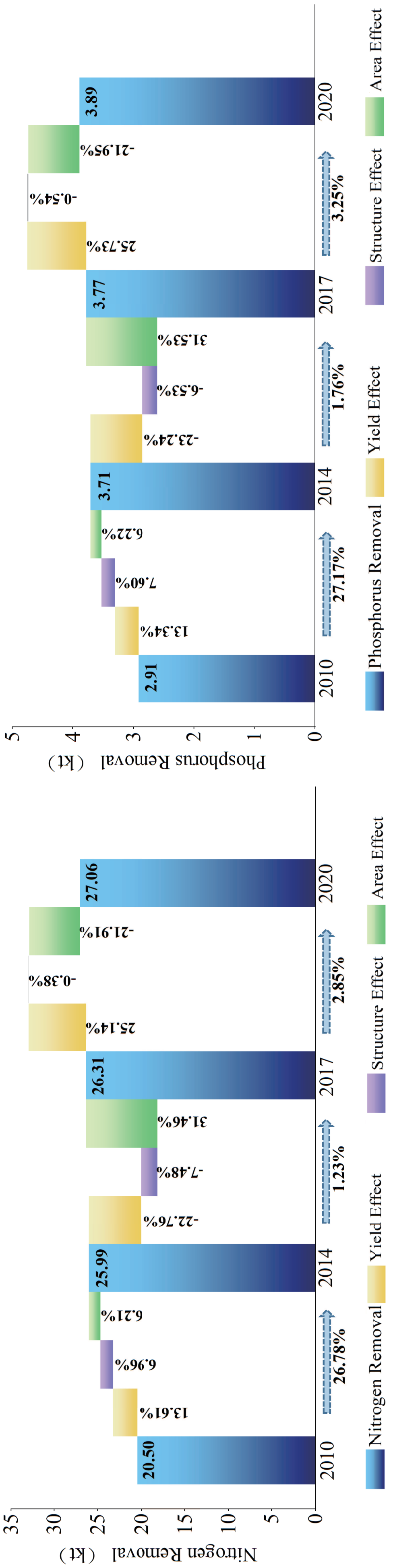

Fig. A2. Uncertainties in carbon sink and nutrient removal of mariculture algae between 2010 and 2020.

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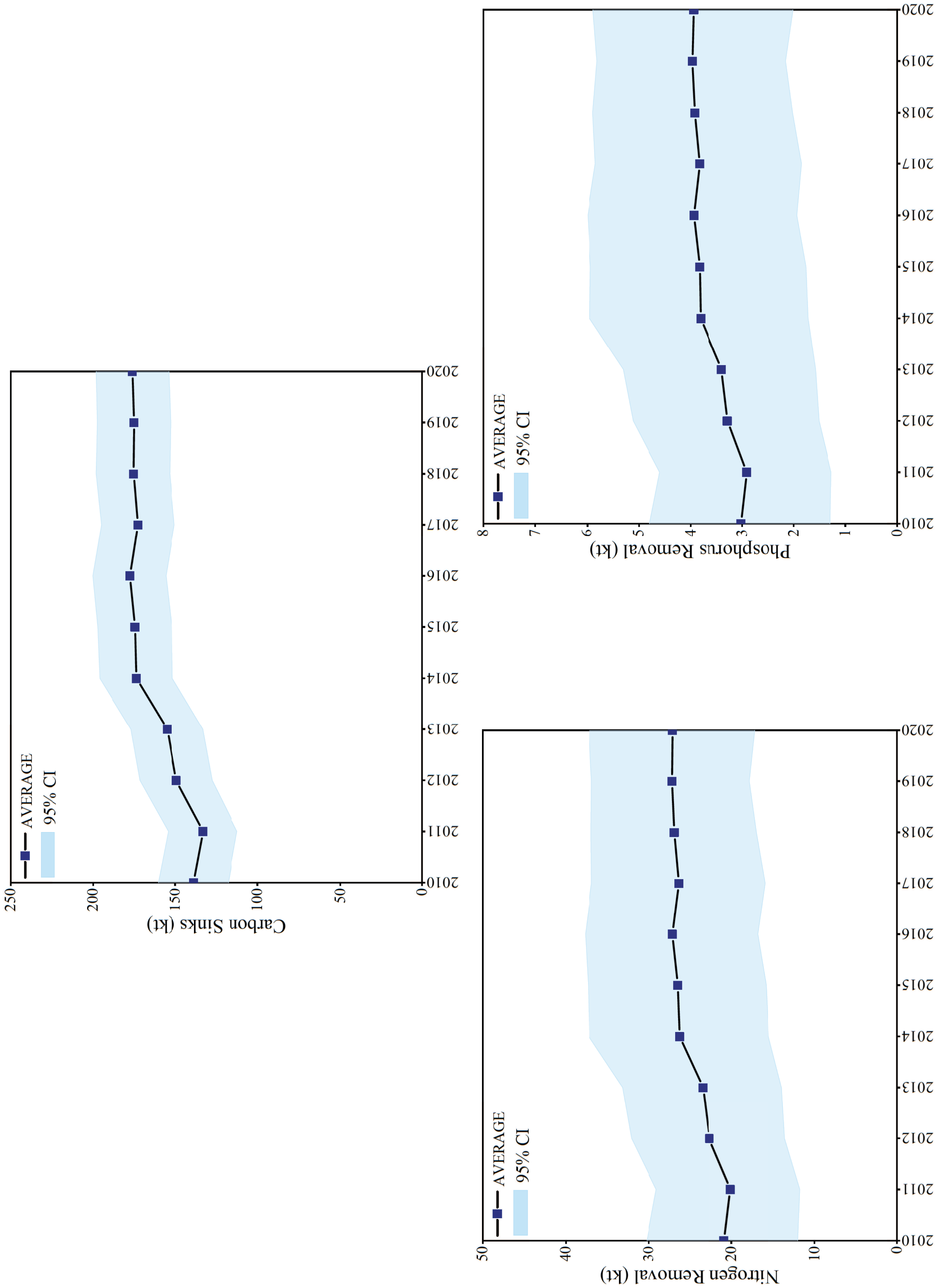

Declaration of Interest Statement

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.