Review

Sustainable Approaches to Realize Carbon Neutrality in China: A Case Study of Zhejiang Province

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Abstract: With the continuous development of industry, the massive emission of carbon dioxide (CO₂) has become a global challenge that cannot be ignored due to its nature as the primary driver of global climate change and environmental crisis. Carbon neutrality is proposed as a global initiative to mitigate climate change. As a developing industrial country, China provides about one-third of global carbon emissions and has set a carbon-neutral goal by 2060. To achieve this goal, continuous efforts across the country are required. In this review, Zhejiang Province, one of the most developed regions in China, is set as a model for analysis. We first summarize the current situation of carbon emission in Zhejiang Province. Then, corresponding sustainable approaches such as ecological and industrial solutions for the reduction of future carbon emissions are introduced for Zhejiang Province. We also provide a direction for the realization of carbon neutrality, focusing on the most promising solutions for Zhejiang Province.

Keywords: carbon neutrality; sustainable technology; carbon capture and utilization; carbon sequestration; sustainability

1. Introduction

The increasing emission of CO₂ causes global warming and ocean acidification, imposing damages on the global ecosystem. With the continuous development of industry, fossil CO₂ emissions have increased rapidly (Figure 1a), and global fossil CO₂ emissions have reached 36.4 Gt yr⁻¹ in 2021 [1]. In response to the increasing global warming, climate goals, i.e., “zero carbon” and “carbon neutral”, have been proposed by more than 130 countries in the world [2] while 66 of them have reached a consensus on the net-zero target [3]. The specific content of carbon neutrality was discussed at the 26th United Nations Climate Change Conference of the Parties (COP26), the goals of which are achieving global net-zero CO₂ emissions by mid-century and trying best to control the increase in temperature to within 1.5 °C, adapting to protect communities and tackle challenges of climate changes, mobilizing finance, and coordinating efforts [4]. In addition, many countries have pledged to stop net deforestation by 2030 and consolidated global consensus on accelerating climate action [5]. However, only 4.5% of countries are carbon neutral and the challenges are daunting yet inevitable for the long-term shared future for all human beings.

The Intergovernmental Panel on Climate Change (IPCC) defines carbon neutrality as “anthropogenic CO₂ emissions balanced globally by anthropogenic CO₂ removals over a specified period”. To achieve carbon neutrality, it is necessary to reduce carbon emissions and increase carbon sequestration by enhancing the absorption of CO₂. Considering the vast amount of CO₂ emissions produced each day, neutrality will remain a target more than an accomplishment without carbon-negative technologies.

China, the biggest carbon emitter with a coal-dominated energy structure [6], promised to peak its emissions by 2030 and achieve carbon neutrality by 2060. The fossil CO₂
emissions in China reached $10.67 \text{ Gt yr}^{-1}$ in 2020, accounting for about one-third of global fossil CO$_2$ emissions [7]. As a large industrial province, Zhejiang provided $381.4 \text{ Mt yr}^{-1}$ CO$_2$ emissions according to the IPCC sectoral approach in 2019, accounting for 3.89% of the CO$_2$ emissions in China. In this review, the present conditions and the possible solutions in the future are discussed in Zhejiang, China.

Figure 1. CO$_2$ emissions. (a) Fossil CO$_2$ emissions of the world from 1956 to 2021 and China from 1956 to 2020. The line shows the proportion of fossil CO$_2$ emissions in China to that in the world. Data source: The data from 1956 to 2020 was obtained from the Global Carbon Project (https://doi.org/10.18160/gcp-2021, accessed on 1 May 2022) and the fossil CO$_2$ emissions of the world in 2021 were obtained from the Global Carbon Budget 2021 [1]. (b) Range of total apparent CO$_2$ emissions by province in China from 1997 to 2019. The red line represents the situation in Zhejiang. (c) The current situation for CO$_2$ emissions in Zhejiang Province is divided into several sections. (d) The percentage of each section for Zhejiang Province in China from 1997 to 2019 (source: https://www.ceads.net.cn, accessed on 22 April 2022).

2. De-Carbonization by Nature

2.1. Understanding of Carbon Sink: The Current Status of the Natural Environment

Zhejiang Province plays an important role in China’s economy. It is located on the east coast of China, with forests, rivers, lakes, mangroves, coastal sea, and many other natural ecosystems. The coastal area of Zhejiang Province also receives material from the Changjiang River estuary. The study of natural carbon sinks in Zhejiang Province is significant for us to obtain an understanding of China and even the world. Zhejiang Province carried out the third national land survey from September 2018, comprehensively investigating land use in the whole province. In this part, the natural environment of
Zhejiang Province is divided into 8 parts, the carbon sink of each part is calculated based on existing research results, and the data from different sources are analyzed and discussed (Figures 2–4, Table 1). The reported carbon sequestration capacity of particular ecosystems may vary by an order of magnitude in different studies due to different sampling sites, sampling methods, simulation precision, and analysis methods. Therefore, to better reflect the carbon sequestration capacity of local ecosystems in Zhejiang Province, this review used data from direct studies on Zhejiang Province as far as possible. For some ecosystems with little research available on Zhejiang Province, such as lakes and mangroves, the data from studies on nearby provinces (such as Guangdong, Fujian, Shanghai, and Jiangsu) were used instead as specified. After obtaining the carbon sink rate of the ecosystem, the overall annual carbon sequestration capacity of the ecosystem is calculated by multiplying the area size and carbon sink rate of the ecosystem. All the data on carbon sink rates from different studies are indicated with sources.

2.1.1. Terrestrial Ecosystem

One of the easiest approaches to increase the carbon sink is to plant trees, but 58.2% of Zhejiang Province’s area is forest, which means the afforestation potential is low. After years of development and utilization, young- or middle-aged trees account for 76.76% of Zhejiang Province’s forest area, which has a low carbon storage density but a higher growth rate than old forests [8,9]. If reasonable forest management is adopted, the carbon density of young- and middle-aged forests will increase gradually, thus improving the carbon fixation ability of the forest ecosystem in Zhejiang Province [10]. The Natural Forest Protection Project initiated in 1998 has contributed to the carbon sink of China. From 1998 to 2010, the projects contributed 889.1 Mt C [11]. The calculation of the forest carbon sequestration rate is mainly based on the forest carbon density [8,12]. One method is to divide the forest into different stages according to age and assume that the growth rate of the carbon density in each stage is constant. The forest in Zhejiang Province is mainly middle-aged, and the growth rate of the carbon density is 137 t C km\(^{-2}\) yr\(^{-1}\), which is equivalent to a carbon sequestration rate of 502.33 t CO\(_2\) km\(^{-2}\) yr\(^{-1}\) [8]. A study based on the continuous biomass expansion factor model calculated that the total forest biomass carbon stock in Zhejiang Province was 97.44 Mt from 2004 to 2008 and 120.45 Mt from 2009 to 2013 [12]. Currently, the total forest area of Zhejiang Province is 6.1 \times 10^4 km\(^2\), so the average forest carbon sequestration rate of Zhejiang Province is 276.35 t CO\(_2\) km\(^{-2}\) yr\(^{-1}\). The two studies were similar, but both were below the global average of 1192.40 t CO\(_2\) km\(^{-2}\) yr\(^{-1}\) (Figure 2a) [13].

| Type                | Area (km\(^2\)) | Carbon Sink Rate (t CO\(_2\) km\(^{-2}\) yr\(^{-1}\)) | Carbon Sequestration Capacity (t CO\(_2\) yr\(^{-1}\)) |
|---------------------|-----------------|-----------------------------------------------------|-----------------------------------------------------|
| Coastal sea         | 260,000         | 53.90–6022.98                                       | 1.40 \times 10^7–1.57 \times 10^9                   |
| Forest (without bamboo forests) | 52,000         | 275.35–502.33                                       | 1.44 \times 10^7–2.61 \times 10^7                   |
| Bamboo forest       | 9060            | 277.90–294.40                                       | 2.52 \times 10^6–2.67 \times 10^6                   |
| Tidal flat          | 1580            | 84.33–784.67                                        | 1.33 \times 10^5–1.24 \times 10^6                   |
| Saltmarsh           | 180             | 375.22–6453.33                                      | 6.75 \times 10^4–1.16 \times 10^6                   |
| Lakes               | 2200            | 52.40–125.77                                        | 1.15 \times 10^5–2.77 \times 10^5                   |
| Reservoirs          | 1300            | 122.47–1067                                         | 1.59 \times 10^5–1.39 \times 10^6                   |
| Mangrove            | 0.2             | 320.28–3374                                         | 64.1–675                                             |

Table 1. A summary of terrestrial and marine carbon sinks in Zhejiang Province.
Figure 2. Carbon sink rates in terrestrial ecosystems from different studies. (a) Forest and bamboo forest; (b) lakes and reservoirs. Source of data: Yang et al., 2022, global average forest carbon sink rate [13], for comparison, not used in the final forest carbon sequestration rate range in Zhejiang Province; Chen et al., 2022b, the growth rate of natural-forest carbon density in the pre-mature and mature stage [8]; Zhao et al., 2019, total forest biomass carbon stocks in Zhejiang Province in different years [12]; Guo et al., 2013, total bamboo forest biomass carbon stocks in Zhejiang Province in different years [14]; Li et al., 2018, total bamboo forest aboveground biomass carbon stocks in Zhejiang Province in different years [15]; Zhang et al., 2017, 7 lakes from Jiangsu, Shanghai [16]; Phyoe et al., 2020, Xin’anjiang Reservoir from Zhejiang Province [17]; Mendonca et al., 2017, the median global carbon sink rates of lakes and reservoirs [18].

At the same time, Zhejiang Province has a considerable number of bamboo forests, accounting for 15% of the total amount of forest land. Owing to their rapid growth rate and reproductive capacity, bamboo forests have a higher carbon sink rate than other subtropical forests [15]. The bamboo forest is especially proposed when calculating the forest carbon sequestration rate in Zhejiang Province in this review. The carbon density of bamboo forests in Zhejiang Province is the lowest (9698 t·km⁻²), lower than the average of 12,080 t·km⁻² [10]. From 2004 to 2008, the carbon stock of bamboo forests in China was 1.99 × 10⁸ t C with an area of 5.48 × 10⁴ km², and from 1999 to 2003, it was 1.77 × 10⁸ t C with an area of 4.84 × 10⁴ km² [14]. So, the average bamboo forest carbon sequestration rate of Zhejiang Province is 294.40 t CO₂ km⁻² yr⁻¹. The underground biomass of bamboo is also important plant phytolith-occluded carbon (highly refractory organic carbon occluded in the amorphous silica) storage [19]. According to the remote sensing data of bamboo forests in Zhejiang Province, aboveground carbon storage of bamboo forest in 2008 and 2014 was 1.684 × 10⁷ t C and 1.272 × 10⁷ t C, respectively [15]. The average bamboo forest carbon sequestration rate of Zhejiang Province is calculated as 277.90 t CO₂ km⁻² yr⁻¹. The carbon sequestration rates of the above two studies are similar (294.40 and 277.90 t CO₂ km⁻² yr⁻¹, respectively), but the estimates of carbon storage in Zhejiang Province differ by about an order of magnitude (Figure 2a). The reason is that the carbon density of the two studies is different: the former is 5310–8190 t km⁻² and the latter is 1095–1907 t km⁻² [14,15]. The carbon sequestration rates are similar between the whole forest and the bamboo forest. Although bamboo is a good carbon sequestration plant, intensive management strategies such as high-frequency fertilization and the removal of non-bamboo plants will not greatly improve its carbon sequestration capacity [20]. Non-native fast-growing tree species such as Pinus, Picea, Populus, and Eucalyptus are widely grown in China [21]. However, these non-native fast-growing trees may consume more soil water and nutrients and suffer a lot from pests and pathogen outbreaks [22]. More effective strategies such as reduced frequent soil reclamation and a combination of native bamboo and non-bamboo plants should be employed to manage carbon sequestration. The carbon sinks obtained by forests cannot be retained over longer time scales. The production of biochar from biomass is a useful
method to solve the problem [23]. Compared with biomass, biochar is more stable and can endure longer to maintain the carbon sink [24].

Reservoirs and lakes play an important role in global carbon sequestration. Organic carbon in reservoirs and lake sediments originates from either terrestrial sources or the absorption of CO$_2$ by aquatic plants in water bodies and sequestration by sedimentation [17]. The first annual estimate of global lake and reservoir carbon sequestration was 150 Mt C, of which reservoirs accounted for about 40% [18]. Due to the lack of lake data from Zhejiang Province, the average data of seven lakes (Gucheng Lake, Dianshan Lake, Yangcheng Lake, Dongping Lake, Shijiu Lake, Hongze Lake, and Taihu Lake) from Jiangsu and Shanghai were used instead (Figure 2b). The carbon sequestration rate data for these lakes can be calculated in two ways. One is the product of dry mass accumulation rates and organic matter content, and the other is the product of linear sediment rates, porosity, and dry sediment density [16]. The carbon sequestration rates of these seven lakes range from 48.11 to 125.77 t CO$_2$ km$^{-2}$ yr$^{-1}$ (Figure 2b). Similar to the lakes, a combination of sediment coring and the seismic survey was used to confirm the organic carbon bury rate and sediment composition in the Xin’anjiang Reservoir [17]. The organic carbon bury rate in the Xin’anjiang Reservoir ranges from 20 to 43 t C km$^{-2}$ yr$^{-1}$ with an average value of 33.4 t C km$^{-2}$ yr$^{-1}$, which is equivalent to the carbon sink rate of 122.47 t CO$_2$ km$^{-2}$ yr$^{-1}$ [17]. The carbon sink rate of Xin’anjiang Reservoir is not significantly higher than that of the 7 lakes, and lower than the median of the global reservoir (Figure 2b). This may be because Xin’anjiang Reservoir has a high surface area of 567 km$^2$ [17]. The accumulation rate of organic carbon in sediments is negatively correlated with the lake area because small reservoirs tend to be eutrophic [25]. Reservoirs trap rivers containing large amounts of organic particles through dams. This allochthonous organic matter originally travel along rivers to lakes, estuaries, and oceans before reservoirs are built. During transportation, some organic matter is decomposed and mineralized into CO$_2$, which is released into the atmosphere. The establishment of the reservoir makes these particles quickly settle in the reservoir, avoiding contact with the upper oxygen-containing water. Anaerobic bacteria also convert organic matter into greenhouse gases such as methane in anoxic conditions. Therefore, the carbon sink capacity of the reservoir needs to consider these two factors [26]. The construction of a large number of reservoirs has also greatly affected the rate of organic carbon burial in river estuaries, and re-exposure and decomposition of organic carbon from eroded delta sediments also contribute to organic carbon loss [27]. Taking into account drawdown areas caused by falling water levels as the water dries up, the ratio of carbon emissions to carbon sequestration in reservoirs is 2.02 (1.04–4.26), meaning the reservoir has shifted from being a carbon sink to a carbon source [28]. Climate warming lake eutrophication caused by agricultural activities has increased the rate of organic carbon sequestration in Chinese lakes [29].

2.1.2. Marine and Nearshore Ecosystems

Zhejiang Province has special and extensive coastal ecosystems, the salt marshes and tidal flats areas of which rank second in China [30]. Compared to terrestrial ecosystems, marine and nearshore ecosystems are more complex. The research data on the same marine and nearshore ecosystems may vary widely. The lack of a unified field sampling and laboratory analysis method results in a large gap in the measurement of the carbon sequestration rate [31]. Some ecosystems, such as mangroves, have not been studied directly in Zhejiang Province. Therefore, this review selected data from Zhejiang, Jiangsu, Shanghai, Fujian, and Guangdong provinces to determine the range of carbon sequestration rates for these ecosystems (Figure 3).
Figure 3. Carbon sink rates in marine and nearshore ecosystems from different studies. (a) Mangrove; (b) saltmarsh; (c) tidal flat; (d) coastal sea. Source of data: Kang et al., 2008, carbon sequestered by the net productivity of mangroves in Guangzhou [32]; Zhang et al., 2013, carbon sink capacity of mangroves in different areas of China [33]; Yang et al., 2014, mangrove coasts of the Leizhou Peninsula, in Guangdong [34]; Zhu et al., 2016, mangrove wetland in Zhanjiang Gaoqiao, Guangdong [35]; Lunstrum and Chen, 2014, Futian National Nature Reserve on Shenzhen Bay, in Shenzhen, Guangdong [36]; Hu et al., 2019, mangroves in Qia Island, Guangdong [37]; Shao et al., 2013, the coastal wetland of three dominant marsh plants in Hangzhou Bay, Zhejiang [38]; Xu et al., 2014, soil organic carbon storage of the coastal wetlands and tidal flats in Yancheng, Jiangsu [39]; Mei and Zhang, 2008, *Phragmites australis* in the east beach of Chongming Island, Shanghai [40]; Chen et al., 2020a, tidal flats of Shanghai Chongming, Zhejiang Cixi, and Fujian Jiulong River estuary [31]; Jiao et al., 2018, carbon sink in the ECS (the East China Sea) based on net primary productivity [41]; Deng et al., 2006, sediment accumulation and carbon burial in the ECS [42]; Guo et al., 2015, air–sea CO$_2$ fluxes in the ECS [43].

Figure 4. The range of the carbon sink rate and carbon sequestration capacity in Zhejiang Province. (a) The range of the carbon sink rate; (b) the range of the carbon sequestration capacity. Ranked according to the upper limit of the carbon sequestration capacity.
As a type of blue carbon ecosystem, mangrove is located at the boundary of land and sea. The developed root system of plants reduces soil erosion, and the sediments covered by seawater are in anoxic conditions [31]. Meanwhile, the probability of forest fire among mangroves is lower than that of land forest. These features make mangroves have a higher carbon sink capacity than other terrestrial ecosystems [44,45]. However, Zhejiang has a small area of mangroves, i.e., 0.2 km². Despite the high carbon sink rate, mangrove does not play a vital role in the carbon neutrality of Zhejiang Province. The carbon sequestration rate of mangroves is calculated mainly based on the net primary productivity of mangroves [32,33], sediment core sampling [34–36], and the annual carbon density variation of mangroves [37] (Figure 3a). Sediment sampling data are generally lower than the other two, possibly because carbon fixed by plants is oxidized and decomposed in soil or transported horizontally by water flow [33].

The carbon sequestration capacity of salt marsh plants is calculated similarly to that of mangroves (Figure 3b). The carbon sink rates of *Phragmites australis*, *Spartina alterniflora*, and *Scirpus maritimus* in Hangzhou Bay, Zhejiang Province were 6882, 6802, and 1005 t CO₂ km⁻² yr⁻¹, respectively [38]. The typical reed zone wetland in Changjiang Estuary has a strong carbon sink rate, ranging from 4070 to 8836.67 t CO₂ km⁻² yr⁻¹ [40]. The carbon sink rate based on the organic carbon storage of the soil in Yancheng saltmarsh is 375.22 t CO₂ km⁻² yr⁻¹ on average [39]. Tidal flats have low vegetation coverage and are not generally considered to be a high carbon sink; however, they continue to receive deposition processes from estuaries and coastal zones and thus have a carbon sequestration capacity comparable to that of blue carbon ecosystems, which ranges from 84.33 to 784.67 t CO₂ km⁻² yr⁻¹ (Figure 3c) [31,39]. The tidal flat deposits in Zhejiang Province are heavily fed by the Changjiang River. At the same time, human land reclamation and the construction of coastal defense walls have accelerated the rate of carbon sequestration in tidal flats [31].

Although the accuracy and resolution of carbon sink data for nearshore ecosystems still need to be improved, it is a clear fact that these ecosystems play an important role in achieving carbon neutrality. The other harsh reality is that climate change and human activity are also destroying them. Climate change will have a strong impact on gene expression and cellular and whole-organism physiology, leading to recombination and the migration of communities in different regions, and ultimately altering ecosystem services and functions [46]. Because of the sea-level rise caused by global warming, nearshore ecosystem areas are being destroyed. The sequestered organic carbon is re-released to water bodies or ground surfaces, where it is re-broken down into CO₂ and released into the atmosphere. Converting mangroves for agriculture or aquaculture releases carbon that has already been sequestered [44]. Human emissions of excess nutrients lead to the eutrophication of water bodies, which leads to algal blooms. Water hypoxia caused by algal blooms will further affect the respiration and nutrient transport of plant roots, resulting in plant death. These two factors are squeezing nearshore ecosystems areas, which decreases their carbon sequestration potential. In addition to the ecological significance of improving the human living environment, the protection of nearshore ecosystems can also obtain carbon credits by confirming the value of carbon sinks in the carbon trading market, which can promote the restoration of the nearshore ecosystems through market factors. China has launched the Fengxian Coastal Salt Marsh Restoration Project and the Western Jinsan Citizen Beach Consolidation and Restoration Project at the Northern Hangzhouwan Bay in Shanghai, funded by the *National sea-use fees* and *Central islands and sea protection funds* [47].

The ocean is an important regulator of the carbon cycle, which has absorbed approximately 30% of anthropogenic CO₂ since the industrial revolution, helping to buffer climate change [48]. The ocean sequesters carbon by dissolving it in seawater and turning it into ions (the solubility pump); a small part of the organic matter fixed by plankton is deposited and sealed into the sediment through excrement and biological debris (biological pump). Biosynthetic calcium carbonate shells consume carbonate (carbonate pump). Recalcitrant dissolved organic carbon from DOC and POC is converted by microorganisms (microbial
carbon pump) [41,49,50]. Although marginal seas account for 8% of the world’s oceans, the annual CO$_2$ uptake accounts for 10–20% of the total amount of global oceanic annual CO$_2$ uptake [51]. However, projections of the impact of future warming on marine productivity generally indicate a reduction in subtropical productivity [49].

The waters administered by Zhejiang Province are part of the East China Sea (ECS), and the main sea area is located in the south of the Changjiang Estuary. Because most of the current studies are focused on the whole ECS, this review aims to estimate and calculate the carbon sink in the Zhejiang Sea (ZS) area by converting the area of the two sea areas to a proportional scale ($5 \times 10^5$ km$^2$ for ECS, $2.6 \times 10^5$ km$^2$ for ZS). The carbon sequestration capacity of the ECS is affected by the east Asian monsoon, the Kuroshio, and the runoff from the Changjiang River [41]. The Changjiang plume and the coastal area of Zhejiang are sinks of atmospheric CO$_2$ in winter, spring, and summer while autumn is a source of atmospheric CO$_2$ and the shelf is an atmospheric CO$_2$ sink in the cold season and a source of atmospheric CO$_2$ in the warm season [43,52]. The Changjiang plume and coastal areas of Zhejiang are mainly affected by the Changjiang River while the continental shelf is mainly affected by temperature [52]. However, there are some differences between Song et al.’s analysis of the carbon sink in different regions of the East China Sea in different seasons and Liu et al.’s analysis, mainly in winter and summer, during which the nearshore area is a carbon sink or carbon source [52,53]. The reason for the difference may be the division of coastal and continental shelves. The following analysis was mainly based on Song et al.’s viewpoint [53].

In winter and summer, air-sea CO$_2$ exchange processes are relatively regular because of the relatively stable environmental conditions. In winter, due to the upwelling caused by the monsoon, pCO$_2$ in the Changjiang plume and the coastal areas of Zhejiang is higher, which is the carbon source. The continental shelf acts as a carbon sink by absorbing CO$_2$ from the surface of the ocean due to low temperatures and photosynthesis. In summer, a great amount of terrestrial discharge leads to turbidity in the Changjiang plume and the water in the coastal areas of Zhejiang, resulting in low photosynthetic efficiency. Additionally, the mineralization of the discharged organic matter produces CO$_2$, which is represented as a carbon source. As the distance from land increases, the body of water gradually becomes clear. The efficient photosynthesis in the continental shelf consumes a large amount of CO$_2$, which is represented as a carbon sink. In spring and autumn, hydrological conditions are not in a stable state, and the distribution of CO$_2$ sources and sinks fluctuates greatly. In spring, the carbon source and sink are similar to that in summer due to the increase in temperature and runoff in the Changjiang River. In autumn, due to the upwelling and temperature drop, the stratification degree of the water body decreases. The bottom water can be exchanged more easily with the surface water. The CO$_2$ accumulated in the bottom water in spring and summer returns to the air and forms the carbon source.

Although there are some differences, both reviews are relatively uniform regarding the overall situation of the carbon sink and source in the ECS. The calculation of air-sea CO$_2$ flux shows that the ECS is a carbon sink in spring, summer, and winter but a carbon source in autumn. The average CO$_2$ flux of the ECS is $-6.9$ mmol CO$_2$ m$^{-2}$ d$^{-1}$, which is equivalent to the carbon sink rate of 80.45 t CO$_2$ km$^{-2}$ yr$^{-1}$ [43]. This method is similar to the data calculated for seafloor sediments, which are 53.90 t CO$_2$ km$^{-2}$ yr$^{-1}$ [42]. However, the carbon sink rate calculated from the primary productivity of the sea surface differs greatly from the first two data (Figure 3d) [41]. One of the problems with marine carbon sinks in Zhejiang Province is that there is no high-resolution carbon sink distribution map in current studies. The ECS under the jurisdiction of Zhejiang Province is mainly coastal. The estimate may be higher than the actual figure.

The problem that needs to be solved for high-resolution carbon sink maps is the division of sea areas. It is mainly divided into two aspects: law (the sea area under the jurisdiction of each country and place determined by law) and geography (the natural division of sea area determined by geography). According to the 1982 United nations convention on the law of the sea, the current division of maritime areas is the territorial sea,
contiguous zone, exclusive economic zones, and high seas. Twelve nautical miles from the base of the territorial sea is the territorial sea. Twelve nautical miles from the outer edge of the territorial sea is the contiguous zone. An exclusive economic zone is an area adjacent to the territorial sea of a coastal state beyond its territorial sea and its width does not exceed 200 nautical miles from the baseline. The seas outside the exclusive economic zone are the high seas.

Here, we summarize the terrestrial, marine, and nearshore ecosystems’ carbon sinks in Zhejiang Province (Table 1, Figures 4 and 5). Among them, coastal seas and forests have the highest carbon sequestration capacity. The range of the carbon sink rate of terrestrial ecosystems is smaller than that of marine and nearshore ecosystems, indicating that the studies on terrestrial ecosystems are more thorough and clearer.

![Figure 5. The current annual carbon sink status of the natural environment in Zhejiang Province. I. Terrestrial ecosystem. (A) Forests (without bamboo forest); (B) Bamboo forest; (C) Lakes; (D) Reservoirs; II. Marine and nearshore ecosystems (E) Mangrove; (F) Saltmarsh; (G) Tidal flat; (H) Coastal sea.](image)

2.2. Increasing Carbon Sink: Strategies and Approaches

2.2.1. Terrestrial Ecosystem

The land use in Zhejiang has changed since 1970, with a decrease in farmlands and grasslands. On the contrary, the area of construction land has continued to increase, which not only leads to an increase in carbon emissions but also reduces the soil organic carbon (SOC) storage [54]. Controlling the increase in construction land is necessary to reduce carbon emissions in Zhejiang Province.

Forests and grasslands are considered the most important terrestrial carbon sinks [55]. With the Grain for Green Program (GGP) and afforestation, the carbon sink of China was enhanced with the increase in forests and decrease in farmlands [56]. However, the farmland in Zhejiang Province was only 12,905 km² in 2019, which is already lower than the basic permanent cultivated land [57]. With the limit of farmlands and vacant areas, the GGP and afforestation will be not applicable in Zhejiang in the future. In addition, the age of forests also influences the carbon sink. The old forest has lower net ecosystem
production, and the regenerated forest is the important carbon sink [58,59]. There are currently 65.45 km\(^2\) of abandoned mining area in Zhejiang Province, and 7.98 km\(^2\) of abandoned mining area had been rehabilitated in Zhejiang Province in 2020 [60]. At this rate, all the mining areas can be rehabilitated by 2030. Based on the global maximum carbon sequestration potential of regenerated forests of 1158 t CO\(_2\)-eq km\(^{-2}\) yr\(^{-1}\) [61], the CO\(_2\) sink of rehabilitated abandoned mines will increase by about 0.076 Mt CO\(_2\)-eq yr\(^{-1}\) (Table 2). The carbon sink rate of forests in China is lower than the global rate (Table 2), indicating that forest carbon sinks in China still have a high potential to increase due to proper management. The carbon sink of forests can increase with anthropogenic N deposition even in N-rich tropical forests [62]. It was reported that new N inputs of 2.45 t N km\(^{-2}\) yr\(^{-1}\) provide an increase of 175.08 t CO\(_2\)-eq km\(^{-2}\) yr\(^{-1}\) in carbon sequestration in temperate forest [63]. It is estimated that the 60,936 km\(^2\) of forest in Zhejiang will improve 10.67 Mt CO\(_2\)-eq km\(^{-2}\) yr\(^{-1}\) for carbon sequestration.

### Table 2. Increased carbon sinks (accounting for CO\(_2\)-eq).

| Ecosystem      | Method                          | Carbon Sink (CO\(_2\)-eq) per Unit | Increasing Carbon Sink (Mt CO\(_2\)-eq yr\(^{-1}\)) |
|---------------|---------------------------------|-----------------------------------|-----------------------------------------------|
| Farmland      | Proper N fertilizer              | 97.7 t km\(^{-2}\) yr\(^{-1}\)    | 1.26                                         |
|               | No tillage                      | 195 t km\(^{-2}\) yr\(^{-1}\)   | 2.51                                         |
| Forest        | Rehabilitated abandoned mines   | 1158 t km\(^{-2}\) yr\(^{-1}\)   | 0.08                                         |
|               | New N inputs                    | 175.08 t km\(^{-2}\) yr\(^{-1}\) | 10.67                                        |
| Mangroves     | Planting mangroves              | 599.51 t km\(^{-2}\) yr\(^{-1}\) | 0.004                                        |
| Shellfish     | Increase the production          | 0.3561 t/t shellfish (wet weight) | 0.17                                         |
|                |                                  | 0.2034 t/t algae (wet weight)    | 0.14                                         |
| Phytoplankton | Fertilizing                     | 2896 t CO\(_2\)-eq km\(^{-2}\) yr\(^{-1}\) | NA                                           |
| Total         |                                 |                                   | 14.84                                        |

Cultivated land can be a carbon source and a carbon sink, depending on the agricultural technology and management capabilities [64] and it is still a carbon source in China [65]. An appropriate amount of nitrogen fertilizer can increase the yield and carbon sequestration efficiency of crops, but too much nitrogen fertilizer results in the release of greenhouse gases such as N\(_2\)O and CH\(_4\) from the land. The best N fertilizer is 19 t N km\(^{-2}\), which can increase net carbon sink by about 97.7 t CO\(_2\)-eq /km\(^2\) / crop season compared with the average N fertilizer for rice production in Zhejiang Province (30 t N km\(^{-2}\)) at an intermediate mitigation of CO\(_2\) emissions [66]. Calculating based on the crop season per year and the farmland area, the carbon sinks increase by 1.26 Mt CO\(_2\)-eq yr\(^{-1}\). With proper tillage methods such as conservation tillage, the carbon sink of cultivated land can increase. For example, no tillage in the crop residue-returned farming system can increase the soil organic carbon (SOC) by 585 t km\(^{-2}\) total in the 0–60 cm soil depth compared with conventional tillage after 11 years [67]. Based on the rate, the carbon sink can increase by about 2.51 Mt CO\(_2\)-eq yr\(^{-1}\).

### 2.2.2. Marine Ecosystems

Compared with land, the ocean can absorb more CO\(_2\) with a solubility pump and biological pump. The ocean is a natural carbon reservoir and the most important buffer system for changes in the atmospheric CO\(_2\) concentration [68,69]. The total amount of carbon stored in the ocean is about 50 times that of the atmosphere and the average residence time of stored carbon is hundreds of years [70]. As a coastal city, Zhejiang has a vast sea area of 2.6 \(\times\) 10\(^5\) km\(^2\), more than twice the land area. Therefore, the ocean is of great significance for Zhejiang to achieve carbon neutrality.

Current research on ocean carbon sinks mainly focuses on mangroves, seagrass beds, and salt marshes with high biodiversity and primary productivity. According to Table 2, mangrove rehabilitation could increase the carbon sink by 1030.92 t CO\(_2\)-eq km\(^{-2}\) yr\(^{-1}\) based on the average carbon sink rate [33]. Due to the lack of attention given to mangrove
protection, Zhejiang only had 1 km$^2$ in 2019 while the total area of the tidal flats was 1543 km$^2$. According to the special action plan for mangrove protection and restoration, Zhejiang Province needs to increase mangroves by 2 km$^2$ from 2020 to 2025. Based on this increasing rate, mangroves will increase to 5 km$^2$ by 2030 and 17 km$^2$ by 2060. However, because of the limit of the natural environment, it is predicted that there is only 28 km$^2$ at most to plant mangroves in Zhejiang Province [71] and the maximum increase in the carbon sink is only about 0.03 Mt CO$_2$-eq yr$^{-1}$ (Table 2).

Because of the limit of the high requirements for the environment and the narrow areas, increasing mangroves is an inefficient method. Instead, it was reported that the mariculture of shellfish and algae provides a carbon sink in China and the average wet weight carbon sink coefficient of shellfish and algae was 9.72% and 5.55% [72]. The data include the average carbon sink rates for different kinds of shellfish and algae calculated with Equations (1) and (2). It is predicted that the carbon sink of shellfish and algae in Zhejiang will increase in the future [72,73]. The area of mariculture has continued to expand, reaching 825.4 with 364.8 km$^2$ of shellfish and 173.2 km$^2$ of algae. With the expansion of the area, the production of shellfish and algae increased from 2015 to 2020 in Zhejiang Province (Figure 6). Algae production has increased by about 70,000 tons per year while shellfish production has increased by about 50,000 tons per year since 2017. According to the production growth rate, we can estimate an increase in the carbon sink. Most shellfish and algae in China are cultivated in tidal flats and the area of tidal flat culture in Zhejiang Province is 358.15 km$^2$. If all tidal flats are changed to the cultivation of shellfish and algae, the production of shellfish will reach 4.71 Mt and the production of algae will reach 2.57 Mt according to the current culture area ratio, which can provide an increase of 1.29 and 0.40 Mt in the carbon sink:

\[
C_s = p_s \times d_s \times (r_s \times g_s + r_s' \times g_s')
\]

where $C_s$ is the carbon sinks of shellfish; $p_s$ is the production of shellfish; $d_s$ is the dry weight ratio of shellfish; $r_s$ is the quality weight ratio of shell; $g_s$ is the carbon sink coefficient of shell; $r_s'$ is the quality weight ratio of soft tissue; and $g_s'$ is the carbon sink coefficient of soft tissue:

\[
C_a = p_a \times d_a \times g_a
\]

where $C_a$ is the carbon sink of algae; $p_a$ is the production of algae; $d_a$ is the dry weight ratio of algae (20%); and $g_a$ is the carbon sink coefficient of algae.

Phytoplankton can adapt to various environments in the ocean, with a fast growth rate and high contribution to the primary productivity of the ocean. Phytoplankton can convert CO$_2$ into particulate organic carbon (POC) through photosynthesis, and then sink to the deep sea or be eaten by predators to realize carbon storage, which has the potential to improve the ocean carbon sink [75,76]. By fertilizing the sea (such as Fe, Al), phytoplankton in the ocean can be increased, resulting in greater absorption of CO$_2$. The phytoplankton particulate organic carbon (POC) flux can reach 0.77 t CO$_2$-eq km$^{-2}$ d$^{-1}$ when microalgae are not in bloom and 87.94 t CO$_2$-eq km$^{-2}$ d$^{-1}$ when they are in bloom in the East China Sea [77], resulting in about 281.05 t CO$_2$-eq km$^{-2}$ yr$^{-1}$ even without considering the blooming. If 10% of Zhejiang’s sea area is cultivated with phytoplankton, it can increase the carbon sink by 7.3 Mt CO$_2$-eq yr$^{-1}$. Although phytoplankton has great potential in carbon sequestration, the feasibility and ecological impact of fertilizing the ocean remains controversial [78]. Methods used to improve the carbon sequestration of phytoplankton need further study.
Figure 6. The production (wet weight) of shellfish and algae between 2015 and 2020 in Zhejiang Province. The production of algae (wet weight) was calculated by the dry weight of algae and the dry weight ratio of algae (20%). The carbon sequestration was calculated based on the production (wet weight) and the carbon sink coefficient of shellfish and algae, respectively. Data source: Zhejiang Statistical Yearbook 2021 [74].

Based on the above calculation results (Table 2), the change in the area of the terrestrial ecosystem has little effect on the carbon sink, and proper management is the main method used to increase the carbon sink. In the marine ecosystem, mangrove planting, shellfish, and algae culture play a certain role in the growth of carbon sinks. However, the growth of carbon sinks is small and limited by the area. Due to the vast sea area of Zhejiang, increasing the area of phytoplankton in the open ocean may be an effective method to increase carbon sinks, but the effectiveness of fertilizing the ocean to promote the growth of phytoplankton remains to be studied.

3. Innovative Technologies for CO₂ Emission Reduction
3.1. Low-Carbon Technologies

Dominated by coal power, China’s power industry is the world’s largest in terms of electricity generation. It is also the main source of greenhouse gas emissions in China. In 2020, China’s total power generation capacity reached 7.5 trillion kWh, 1.7 times that of the United States [79]. The power sector emitted about 4000 Mt of CO₂, accounting for about 40 percent of China’s total CO₂ emissions. Therefore, to promote sustainable development, low-carbon clean energy is a vital choice for China’s low-carbon transition under the requirements of the global response to climate change. In Zhejiang, the trend was written in the government’s plan as a concerted action (Table 3).
Table 3. Summary of low-carbon technologies for the power sector in Zhejiang Province.

| Program       | Solar Power | Wind Power | Hydropower | Biomass Power | Nuclear Power | Ocean Power |
|---------------|-------------|------------|------------|---------------|---------------|-------------|
| Example       | Wanxiang Solar PV | ZNG Jiaxing No.1 Offshore Wind Farm | Xin’anjiang Hydropower Station | ZNG Longquan Biomass Power Plant | Qinshan Nuclear Power Plant | LHD Tidal Power Generation Project |
| Total Capacity in 2020 (Million kW) | 15.17 | 1.86 | 11.71 | 2.40 | 9.11 | 0.0058 |
| Targets in 2025 (Million kW) | 27.50 | 6.41 | 15.26 | 3.00 | 10.31 | 0.0058 |
| Electrical Share in 2020 (%) | 14.90 | 1.80 | 11.50 | 2.40 | 9.00 | 0.0057 |
| CO₂ emissions per unit (gCO₂/kWh) | 15.9–29.2 | 7.1–8.6 | 40.6–44.4 | 20.0–70.0 | 10.9 | 8 |

The total capacity and targets were obtained from the Zhejiang Province Electricity Development “14th Five-Year” Plan. The CO₂ emissions per unit of low-carbon technologies were obtained from [79] and Environmental Defense Fund: https://m.huanbao-world.com/view.php?aid=138262 (accessed on 10 July 2022).

The CO₂ emissions per unit of electricity generated from fossil energy is 839 gCO₂/kWh for coal, which is significantly higher than those from low-carbon technologies such as nuclear and renewable sources [79]. According to Table 3, among all these mentioned technologies, wind power has the most potential in the power sector for emission reductions theoretically while solar power is the most dominant part in Zhejiang under the current policy due to its fast technological advances and flexible application sites. It is also calculated that more than 40 Mt CO₂ yr⁻¹ will be reduced by these low-carbon technologies according to the Zhejiang Province Electricity Development “14th Five-Year” Plan. However, they are promising and capable of reducing carbon emissions but not achieving carbon neutrality. At present, we are not fully prepared for a “non-fossil future”. This is why negative emissions technologies (NETs) are indispensable.

3.2. Negative Emissions Technologies (NETs)

The vision of carbon peaking and carbon neutrality has set a new direction for China’s decarbonization and placed new demands on NETs. Carbon capture, utilization, and storage (CCUS) is thought to be an essential option, which is capable of abating around one-third of the total carbon emission [6].

CCUS not only achieves near-zero emissions from fossil energy use but also negative emissions via carbon capture and storage from bioenergy (BECCS). Direct air capture (DAC) is another emerging NET with relatively higher costs. The technology is capable of capturing CO₂ directly from the air where it flows through a liquid or solid sorbent functioning as a separation element [80]. In short, the technologies of CCUS enable the capture and separation of CO₂ from sources such as energy use, industrial processes, or air, and transport it to a suitable site for utilization or storage via tankers, pipelines, ships, etc., ultimately achieving emission reduction, this process is illustrated in Figure 7, together with the cost. By 2020, 65 large commercial CCUS facilities had been in operation or under development worldwide, involving numerous carbon capture projects for large power plants in commercial operation [81]. The global status of CCS 2021 shows that the number of commercial CCUS facilities planned, under construction, and in operation reached 135 by September 2021, more than double the number in 2020, which will approximately capture 150 Mt of CO₂ per year when fully completed.
Figure 7. The capture and utilization of CO$_2$ in different ways and their cost range. Abbreviations: CCS, carbon capture and storage; BECCS, bioenergy with carbon capture and storage; DAC, direct air capture [82,83]. China has made great progress in the last decade in terms of CCUS integrated optimization technology. According to the results of the Ministry of Science and Technology’s nationwide calling for CCUS projects, since the first CCUS project was commissioned in Shanxi in 2004, a total of 49 CCUS projects have been commissioned and under construction, concentrated in Eastern and Northern China, where the first million-ton CCUS project, Qilu Petrochemical–Shengli Oilfield, was fully completed at the end of January 2022. The 38 completed ones have sequestered more than 2.0 Mt of CO$_2$, creating a CO$_2$ capture capacity of 2.96 Mt/a.

China accounts for between 13.8% and 15.5% of total CCS in the world in many low-emission scenarios, reflecting the probability of temperature control [84]. However, compared to many foreign countries, which are generally at the stage of commercial application, China is still lagging behind in terms of overall scale, degree of integration, offshore storage, and industrial applications.

For Zhejiang, CCUS is a key project, especially for mineralogical utilization this year. On March 10, the first CCUS project for coal-fired power plants in Zhejiang Province was officially started by Zhejiang Zenergy Lanxi Power Generation Co. The design scale of the project is to capture 15,000 t of CO$_2$ per year. The CO$_2$ captured will be used for
mineralization and provide conditions for the CO\textsubscript{2} utilization technology. This project will explore an effective path for the decarbonization of traditional energy sources and make a positive contribution to the green and low-carbon development of Zhejiang Province.

4. Concluding Remarks and Future Perspectives

The increase in CO\textsubscript{2} emissions results in climate change, which is harmful to human beings and the whole planet; thus, the achievement of carbon neutrality is vital. The current annual carbon sink status of the natural environment in Zhejiang Province is summarized in this review, highlighting the indispensable role of the coastal sea and forest. However, the reported rates of carbon sequestration vary greatly because of the difference in sampling sites, analysis methods, and so on. More research is needed to improve the precision and accuracy of quantifying the carbon sink rate. To realize carbon neutrality, planting mangroves and increasing the mariculture of algae and shellfish will be useful approaches to increase carbon sinks, but it is still not enough to make up for the carbon emissions in Zhejiang Province due to the limitation of appropriate areas. In addition, due to previous destruction and lack of management, the carbon sink function of the ecosystem cannot be realized compared with global carbon sequestration. To achieve carbon neutrality, it is necessary to increase production and effective management in a limited area through scientific and technological means. In addition, phytoplankton in ocean is a potential carbon sink that needs further study to promote phytoplankton growth.

The geographical environment of provinces sited at the large north-south and east-west span of China is unique. Although the data from neighboring provinces can still work due to the similarity between the two provinces, the conclusions of this paper are not fully applicable to other provinces. Specific measures to achieve carbon neutrality should be adapted to the local conditions of each province and region. However, the methodology can be extensively adopted. By analyzing the types and areas of different ecosystems in specific provinces, refining the analysis type, and improving the analysis accuracy, we can profile the specific carbon sink situation of any province. As future studies of carbon sinks continue to come out, we optimistically anticipate that the accuracy of studies on carbon sinks will continue to improve.

For industry-based solutions, low-carbon technologies for the power sector in Zhejiang Province can provide a considerable decrease in carbon emissions, especially solar power. In terms of low-carbon technologies, Zhejiang Province actively promotes supply-side structural reform of the power industry, which results in optimization of the power structure, energy saving, and emission reduction. It is clear that although Zhejiang’s CCUS project started late, the pressure of emission reduction and transformation is forcing more and more companies to seek breakthroughs in CCUS and its commercial operation. It is only a matter of time before major energy-intensive industries such as electric power, petrochemicals, chemicals, building materials, iron, and steel meet with CCUS in Zhejiang.

In short, there is no doubt that the realization of carbon neutrality will require the combination of ecological and industrial pathways and shared efforts by the government to make reasonable planning and adjustments. More discoveries and technological breakthroughs are needed to drive carbon neutrality from concept to reality. We believe a brighter future is promising and achievable under the continuous development of sustainable approaches for Zhejiang Province and China and Mother Earth.

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