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## 海岸带滨海湿地蓝碳管理的研究进展

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**摘要:**【研究目的】自 2009 年“蓝碳”这一概念首次被提出以来, 海岸带蓝碳生境在封存大气 CO<sub>2</sub> 中的重要作用越来越受到世界各国环境科学家、社会科学家和经济学家们的关注, 如何有效管理海岸带蓝碳成为热门话题之一。【研究方法】基于近些年来国内外对海岸带湿地蓝碳管理的研究进展, 本文系统梳理了海岸带湿地蓝碳的储量和分布情况, 并总结了影响海岸带蓝碳生境及其碳库保存的主要因素。【研究结果】中国海岸带地区滨海湿地的蓝碳总量和碳汇潜力巨大, 但随着海岸带地区开发越发频繁, 已对海岸带蓝碳碳汇能力造成了巨大的影响。【结论】本文提出需要综合环境科学、社会科学和经济学, 强化已有蓝色碳汇的保护和管理, 加强对未来新增蓝碳碳汇的潜力评价, 以此提升中国在碳循环、全球气候变化以及碳减排增汇等方面研究的国际地位, 同时为国家相关应对策略与政策提供科学依据, 并能为近来实施的滨海湿地修复工程提供有力支撑。

**关键词:** 蓝碳; 滨海湿地; 碳储管理; 碳埋藏; 海岸带地质调查工程

**创新点:** 从三维度(保护、修复、创造)和三主体(科学家, 政策制定者, 受益者)提出海岸带蓝碳综合管理策略。

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## Research progress on blue carbon management in coastal wetland ecotones

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**Abstract:** This paper is the result of coastal geological survey engineering.

**[Objective]** Since the term “blue carbon” was first used in 2009, the important role of blue carbon habitats in sequestering atmospheric CO<sub>2</sub> has received an increasing attention from environmental scientists, social scientists, and economists all over the world, and how to effectively manage coastal blue carbon has become one of the hottest topics. **[Methods]** Based on recent publications concerned with the sustainable management of coastal wetland ecotones and the services they provide in terms of blue carbon storage, we synthesized current researches regarding blue carbon, the spatial distribution of blue carbon within coastal ecotones, and the factors that control blue carbon sequestration. **[Results]** The total amount of blue carbon and carbon sequestration potential are huge in China's coastal wetlands. However, with the development of coastal zones becoming more and more extensive, a blue carbon sink capacity of coastal zones has been greatly affected. **[Conclusions]** Further studies are clearly needed to identify how a synthesis of environmental, social, and economic issues can facilitate the conservation and management of blue carbon sinks, and strengthen the potential evaluation of new blue carbon sinks in the future. A blue carbon research will improve China's image within the international scientific community that concerns the researches of carbon cycle, global climate change, and mitigation of greenhouse gas emissions. Blue carbon studies will also provide basic scientific understanding needed to identify relevant national strategies and policies with respect to coastal wetland restoration.

**Key words:** blue carbon; coastal wetland ecotones; carbon management; carbon sequestration; coastal geological survey engineering

**Highlights:** The integrated blue carbon management strategy for coastal zones is proposed from three dimensions (conservation, restoration and creation) and three subjects (scientists, policy makers and beneficiaries).

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## 1 引 言

自工业革命以来,人类对化石能源的过度消耗导致大气中温室气体浓度急剧增加。世界气象组织(WMO)2022年公报中显示:2021年大气中二氧化碳浓度达到 $(415.7\pm 0.2)\times 10^{-6}$ ,为工业化(1750年)以前含量的149%;甲烷浓度为 $(1908\pm 2)\times 10^{-9}$ ,为工业化前的262%;一氧化二氮为 $(334.5\pm 0.1)\times 10^{-9}$ ,为工业化前的124%(WMO,2022)。温室气体的急剧增加已经造成全球范围内剧烈的气候变化,对人类社会的生存和可持续发展所产生的威胁日益明显(丁一汇等,2006;IPCC,2018)。合作应对全球气候变化的挑战和积极寻找解决方案,已成为世界范围内科学家、政策制定者及利益攸关方等的广泛共识(秦大河等,2007;Moss et al., 2010)。目前,温室气体“减排”和“增汇”被认为是应对气候变化的重要途径之一(Canadell and Raupach, 2008; IPCC, 2014)。“减排”可以通过政策手段来抑制一定程度

上化石和生物燃料的消耗,而“增汇”则通常需要加大生物圈、水圈和岩石圈与大气圈的相互作用,以此来吸收和存储大气中过量的碳(Nellemann et al., 2009; Mcleod et al., 2011; Canadell and Schulze, 2014; Wang et al., 2021)。

传统意义上,通过陆地上绿色植物的光合作用固定并储存在自然生态系统的植物和土壤里的碳,称为“绿碳”(Mackey et al., 2008)。其实,海洋也是固定碳、储存碳的重要宝库。2009年,联合国环境规划署(UNEP)、联合国粮食及农业组织(FAO)、联合国教科文组织(UNESCO)和政府间海洋学委员会(IOC)联合发布了题为《蓝碳:健康海洋对碳的固定作用—快速反应评估》的报告(Blue Carbon: the Role of Healthy Oceans in Binding Carbon—A Rapid Response Assessment)(以下简称《蓝碳报告》),提出了“蓝碳”(Blue Carbon)这一重要概念,特指由海洋生态系统吸收大气中的二氧化碳并将其固定在海洋中的碳(Nellemann et al., 2009)。《蓝碳报告》指

出,虽然海洋浮游植物生物量虽然只有陆地植物生物量的0.05%,通过光合作用捕获碳总量却占在世界上每年捕获的碳一半以上(55%)。其中海岸带生境,包括海草床、红树林、盐沼等海岸带蓝碳生态系统(图1),虽然面积不到海面面积的0.2%,却约占海洋沉积物有机碳埋藏总量的50%,是生物圈最密集的碳汇之一(Duarte et al., 2005)。近来的研究表明,海岸带地区的大型海藻、贝类甚至微型生物也能高效固定并储存碳(焦念志, 2012; Jiao et al., 2014; Gao et al., 2016; Raven, 2018; 唐剑武等, 2018)。另外,相比起绿碳,海洋生态系统捕获的蓝碳储存时间可长达数千年(McKee et al., 2007; Lo Iacono et al., 2008; Macreadie et al., 2013)。因此,蓝色碳汇及其生境系统对缓解气候变化有巨大的潜力,对沿海地区的气候、人类健康、粮食安全及经济发展都至关重要(Arkema et al., 2013; Duarte et al., 2013)。

虽然人们对海洋碳固存的认知已有30余年,但是之前国内外对于自然生态系统碳汇的关注多集中于陆地生态系统(Dixon et al., 1994; Dean and

Gorham, 1998; Lal, 2004; Deng et al., 2017),近10年来对海洋固碳和蓝碳相关的研究才开始明显上升(Mcleod et al., 2011; 章海波等, 2015; Duarte, 2017; Spivak et al., 2019; Wang et al., 2022)。与此同时,全球蓝色碳汇却在急剧减少,近海富营养化、填海造陆、海岸工程及海岸城市化致使海岸带一部分蓝碳生境消失(Duarte et al., 2008; Duarte, 2009)。固碳生境消失的同时也会导致已储存的碳重新释放到大气中,进一步加重温室效应(Couwenberg et al., 2010; Pendleton et al., 2012; Hamilton and Friess, 2018)。鉴于海洋蓝碳,特别是海岸带蓝碳对缓解气候变化所起的积极作用,本文总结了近20年来国内外海岸带蓝碳的研究进展,重点阐述了影响海岸带蓝碳碳库变化的因素,在此基础上提出相应的管理对策和方针,以此加大中国的蓝碳保护力度,提高中国在国际碳汇市场的发言权,并为缓解气候变化做出中国应有的贡献。

## 2 海岸带蓝碳储量及分布特征

海岸带蓝碳生境类型主要分为红树林、盐沼以

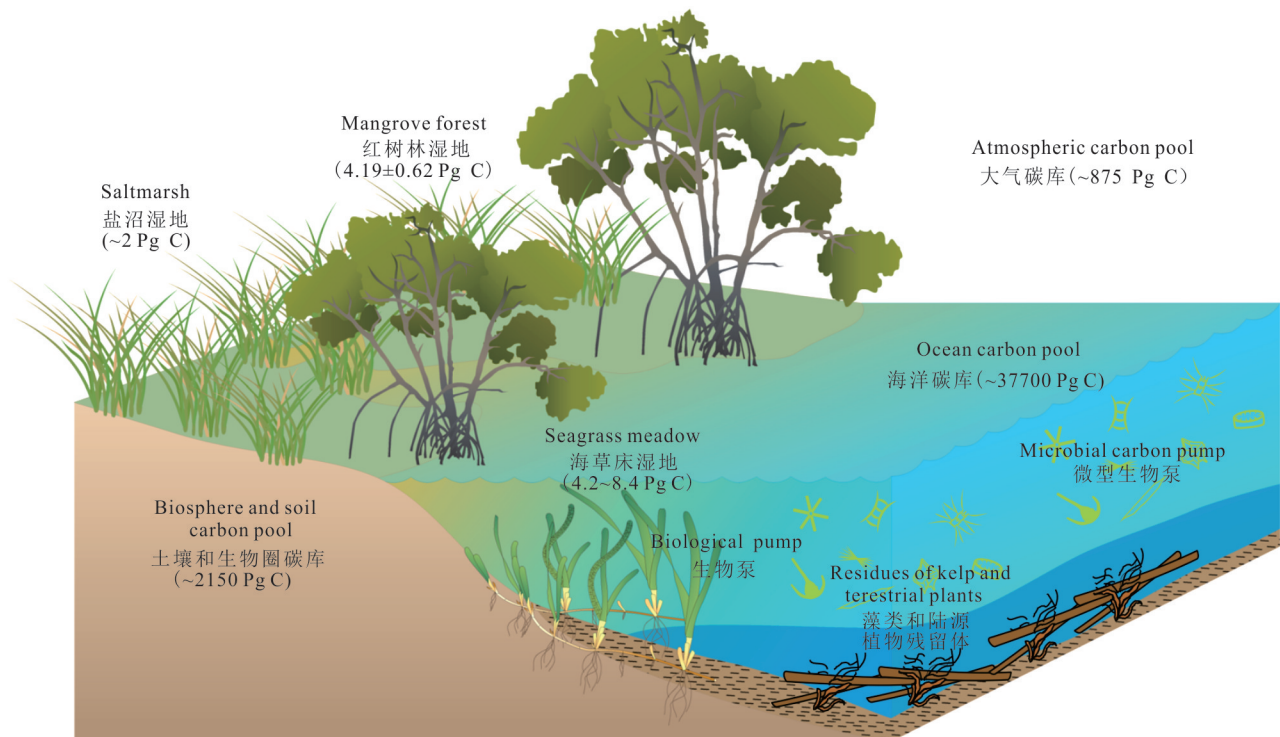


图1 海岸带三大主要蓝碳生境储量估算(据 Macreadie et al., 2019; Friedlingstein et al., 2022 修改)

Fig.1 Estimated carbon storages of three dominated blue carbon ecosystems in coastal areas (modified from Macreadie et al., 2019; Friedlingstein et al., 2022)

表1 全球及主要地区三大主要滨海湿地系统蓝碳储量一览  
 Table 1 Blue carbon stocks of three dominated coastal wetland ecosystems in global and major regions

类型	区域	面积/km <sup>2</sup>	蓝碳总量	1 m以内土壤 平均储量*/ (Mg C ha <sup>-1</sup> )	地上平均 生物量* (Mg C ha <sup>-1</sup> )	地下平均 生物量* (Mg C ha <sup>-1</sup> )	土壤平均 埋藏速率 (g C m <sup>-2</sup> a <sup>-1</sup> )	蓝碳平均 封存潜力 (Tg C a <sup>-1</sup> )	参考文献
	全球	137760 ~166000	(4.19± 0.62) Pg	(2.96±0.53) Pg	(0.82±0.04) Pg	(0.41±0.02) Pg	226(20~949)	(31.1±5.4) ~(34.4±5.9)	Chmura et al., 2003; Hamilton and Friess, 2018; Sanderman et al., 2018
红 树 林	中国	321	162 Tg	344.67±42.23	253.98± 327.28	83.96±77.56	226±39	0.07	张莉等, 2013; Gao et al., 2016; Meng et al., 2019
	印尼	31894	(3.0±0.1) Pg	761.3±73.6	191.2±20.2	21±2.7	—	—	Alongi et al., 2016
	澳大利 亚	3315 ~10509	—	251±155	125±90	—	126±90	0.4~1.4	Serrano et al., 2019
盐 沼	全球	41657 ~400000	~2 Pg	0.67~6.5 Pg	—	—	218±24 (18~1713)	(4.8±0.5) ~(87.2±9.6)	Chmura et al., 2003; Duarte et al., 2005, 2013; Mcleod et al., 2011; Pendleton et al., 2012; Gao et al., 2016
	中国	1200 ~3430	67 Tg	134.37	8.82±6.14	9.95±16.13	235.62	0.75	段晓男等, 2006; 关道明, 2012; Meng et al., 2019
	澳大利 亚	13765 ~15329	—	168±127	7.5±6.1	—	39±30	0.48~0.54	Serrano et al., 2019
海 草	全球	300000 ~600000	4.2~8.4 Pg	329.5±55.9	0.76±0.13	1.76±0.38	138±38 (45~190)	48~112	Duarte et al., 2005; Fourqurean et al., 2012
	中国	87.65	75 Tg	134.37±19.43	0.36±0.15	0.41±0.46	83	—	郑凤英等, 2013; 邱广龙等, 2014; Meng et al., 2019
	印尼	30000	368.5 Tg	118.1	0.29	1.13	—	—	Alongi et al., 2016
澳大利 亚	92569 ~127720	—	112±88	1.9±2.0	—	36±30	2.5~3.5	Serrano et al., 2019	

注: \*除个别数据单独标注外, 未标注单位数据均为 Mg C ha<sup>-1</sup> (1 Mg=10<sup>6</sup>g)。

及海草床三种。全球海岸带蓝碳储存总量约为 10.8~20 Pg C (1 Pg=10<sup>15</sup>g), 平均每年封存碳储约为 0.08~0.22 Pg C a<sup>-1</sup> (Alongi et al., 2016; Gao et al., 2016)。其中中国蓝碳储量在 48.12~123.95 Tg C (1 Tg=10<sup>12</sup>g), 平均每年封存碳储约为 0.84~1.47 Tg C a<sup>-1</sup> (Gao et al., 2016; Meng et al., 2019)。各生境类型分布特征和蓝碳储量估算(表1)如下:

全球红树林(mangrove forest)约占世界陆地总面积的0.1%, 介于137760~166000 km<sup>2</sup>, 主要分布在印度—太平洋赤道地区 (Pendleton et al., 2012; Sanderman et al., 2018)。红树林面积最多的前20个国家占据了全世界80%~85%的比例, 其中印度尼西亚、巴西、马来西亚和巴布亚新几内亚四国占全球红树林面积的50% (Hamilton and Casey, 2016)。全

球红树林2012年蓝碳储量(含地下1 m以内土壤和植物地下和地上部分)约为(4.19±0.62)Pg C, 其中地下1 m以内土壤有机碳含约(2.96±0.53)Pg C (占比70.65%), 地上植被为(0.82±0.04)Pg C (占比19.57%), 地下植物根茎等含(0.41±0.02)Pg C (占比9.87%) (Hamilton and Friess, 2018)。碳埋藏速率介于20~949 g C m<sup>-2</sup> a<sup>-1</sup>, 平均约226 g C m<sup>-2</sup> a<sup>-1</sup>, 每年封存的碳储在(31.1±5.4)~(34.4±5.9)Tg C a<sup>-1</sup> (Chmura et al., 2003; Giri et al., 2011)。中国红树林面积(2013年)面积约3.21万 ha, 主要分布在广东、广西、福建和海南四省(图2; Meng et al., 2019)。中国红树林蓝碳储量(同上标准)约~162 Tg C (Gao et al., 2016), 其中土壤有机碳平均含约(344.67±42.23) Mg C ha<sup>-1</sup>, 地下30~60 cm土壤有机碳平均含量最高

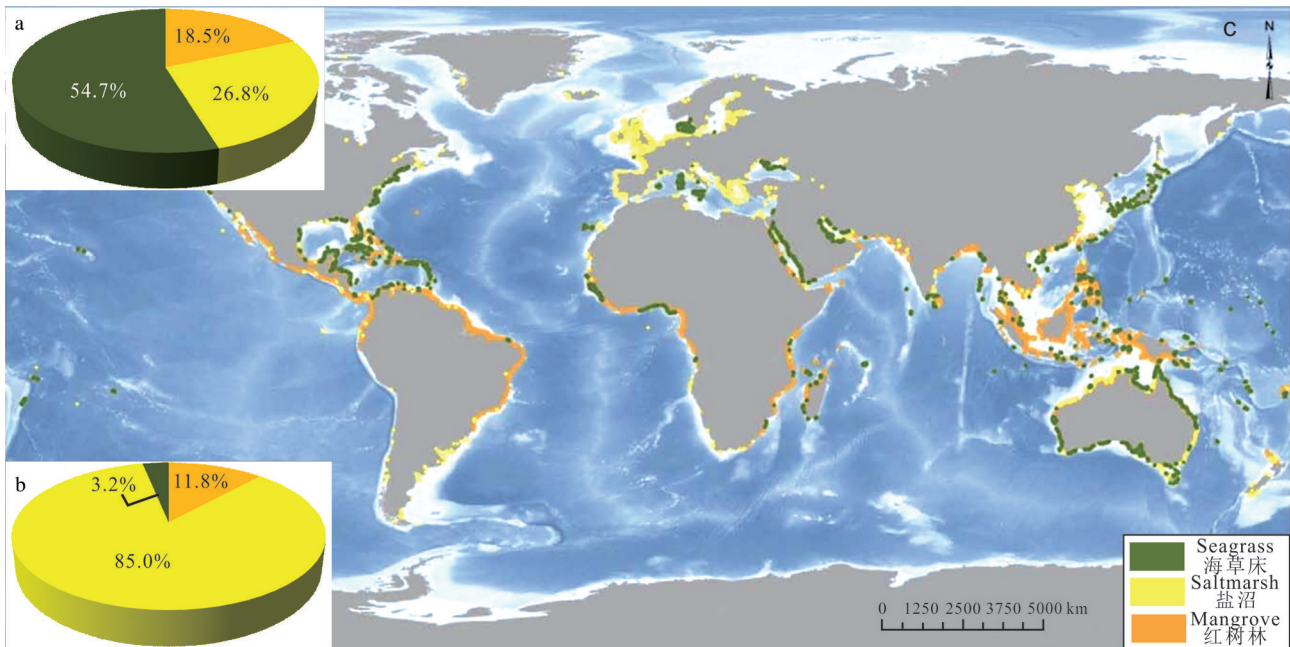


图2 三大蓝碳生境的分布及面积占比(据Pendleton et al., 2012修改)

a—全球三大蓝碳生境面积占比;b—中国三大蓝碳生境面积占比;c—三大蓝碳生境全球分布图

Fig.2 Distribution and areal percentages of three blue carbon ecosystems (modified from Pendleton et al., 2012).

a—Global areal percentages of three blue carbon ecosystems; b—Areal percentages of three blue carbon ecosystems in China; c— Global distribution of three blue carbon ecosystems

( $30\sim 44\text{ g kg}^{-1}$ );地上植被含( $253.98\pm 327.28$ ) $\text{Mg ha}^{-1}$ ,地下植物根茎等含( $83.96\pm 77.56$ ) $\text{Mg C ha}^{-1}$ ,碳埋藏速率约为 $206\sim 661\text{ g C m}^{-2}\text{ a}^{-1}$ (张莉等, 2013),每年封存的碳储约 $\sim 0.07\text{ Tg C a}^{-1}$ (Meng et al., 2019)。

全球盐沼(saltmarsh)湿地面积约 $41657\sim 400000\text{ km}^2$ (Pendleton et al., 2012; Ouyang and Lee, 2014),在中高纬度(通常 $25^\circ\text{N}$ 以北; $25^\circ\text{S}$ 以南)海岸潮间带地区均有分布(图2)。全球盐沼湿地土壤有机碳储量在 $0.67\sim 6.5\text{ Pg C}$ (McLeod et al., 2011),碳埋藏速率介于 $18\sim 1713\text{ g C m}^{-2}\text{ a}^{-1}$ ,平均值在( $218\pm 24$ ) $\text{g C m}^{-2}\text{ a}^{-1}$ (Chmura et al., 2003; Duarte et al., 2005),每年封存的碳在( $4.8\pm 0.5\sim 87.2\pm 9.6$ ) $\text{Tg C}$ (Pendleton et al., 2012; Duarte et al., 2013)。中国盐沼湿地面积约 $1200\sim 3430\text{ km}^2$ ,主要分布于福建以北的各大河口三角洲和泥质海岸带地区(图2),生境类型以芦苇滩、碱蓬滩、海三棱旗草滩和互花米草滩为主(关道明, 2012)。中国盐沼湿地碳储量共计 $\sim 67\text{ Tg C}$ ,其中土壤有机碳 $134.37\text{ Mg C ha}^{-1}$ ,地上植被含( $8.82\pm 6.14$ ) $\text{Mg C ha}^{-1}$ ,地下植物根茎等含( $9.95\pm 16.13$ ) $\text{Mg C ha}^{-1}$ ,碳埋藏平均速率约为 $235.6$

$\text{g C m}^{-2}\text{ C a}^{-1}$ (段晓男等, 2006),每年封存的碳储约 $\sim 0.75\text{ Tg C a}^{-1}$ (Meng et al., 2019)。

全球海草床(seagrass meadow)总面积约在 $300000\sim 600000\text{ km}^2$ ,不到全球海洋面积的 $0.2\%$ (Duarte et al., 2005),主要分布于墨西哥湾沿岸、地中海、印度洋—太平洋赤道和澳大利亚近岸水域(Fourqurean et al., 2012)。全球海草床储存蓝碳总量保守估计有 $4.2\sim 8.4\text{ Pg C}$ ,其中地下 $1\text{ m}$ 以内沉积物中有机碳平均含量约( $329.5\pm 55.9$ ) $\text{Mg ha}^{-1}$ ,地上植被为( $0.76\pm 0.13$ ) $\text{Mg C ha}^{-1}$ ,地下植物根茎等含( $1.76\pm 0.38$ ) $\text{Mg ha}^{-1}$ (Fourqurean et al., 2012)。碳埋藏速率介于 $45\sim 190\text{ g C m}^{-2}\text{ a}^{-1}$ ,平均约( $138\pm 38$ ) $\text{g C m}^{-2}\text{ a}^{-1}$ (95%置信区间),每年封存的碳储在 $48\sim 112\text{ Tg C a}^{-1}$ (Duarte et al., 2005)。中国海草床面积较小,仅约为 $8765\text{ ha}$ ,主要分布于南海和黄渤海海岸附近(郑凤英等, 2013)。中国海草床沉积物埋藏有机碳含量约为( $134.37\pm 19.43$ ) $\text{Mg C ha}^{-1}$ ,地上植被为( $0.36\pm 0.15$ ) $\text{Mg ha}^{-1}$ ,地下植物根茎等为( $0.41\pm 0.46$ ) $\text{Mg C ha}^{-1}$ (Meng et al., 2019)。海草床碳埋藏速率平均速率约为 $83\text{ g C m}^{-2}\text{ a}^{-1}$ (邱广龙等, 2014)。

虽然全世界巨藻(macroalgae)分布面积可达到

340万 km<sup>2</sup>, 初级生产力约 1.5 Pg C a<sup>-1</sup> (Krause-Jensen and Duarte, 2016), 但是因为巨藻大多发育在基岩海底, 无法将有机碳固定在沉积物中, 目前为止还未将巨藻包含在传统意义上的海岸带蓝碳体系中 (Raven, 2018)。不过, 越来越多的证据显示, 巨藻有机质物质可被搬运且被封存在浅海—深海中, 埋藏速率可达 274~312 g C m<sup>-2</sup> a<sup>-1</sup>, 每年封存的碳平均约为 173 Tg C a<sup>-1</sup>, 对全球碳循环和碳储评价有较大的影响 (Krause-Jensen et al., 2018; Macreadie et al., 2019)。另外, 由于巨藻通常具有较高的经济价值, 中国乃至世界其他沿海地带均有大量养殖, 这一部分碳贮也值得进一步关注 (Krause-Jensen et al., 2018; Macreadie et al., 2019)。

贝类和珊瑚礁的钙化过程是个无机碳双向的化学反应过程, 从生命过程和碳循环的全周期来看, 其钙化过程可以影响海洋的碳循环 (唐剑武等, 2018)。如果贝壳养殖后被捕捞并储存在陆地上, 失去淋溶的条件, 贝壳可以成为潜在的碳汇 (Gao et al., 2016; Ahmed et al., 2017)。已有估算的结果显示: 全球贝壳碳固定平均含量达到 62.9 g kg<sup>-1</sup> (Duarte et al., 2005), 而中国贝壳储碳平均含量为 22.7~88.7 g kg<sup>-1</sup>。如按目前中国贝类养殖规模初步计算, 每年中国贝类固碳量可达 0.24~1.1 Tg C (岳冬冬和王鲁民, 2012; Gao et al., 2016)。珊瑚的固碳原理与贝壳类似, 其生境可被称为“海洋动物森林”。Duarte et al. (2005) 估算世界珊瑚礁平均总碳封存速率可达到 148 g C m<sup>-2</sup> a<sup>-1</sup>; 而如果仅考虑有机碳埋藏速率, Coppari et al. (2019) 对地中海地区柳珊瑚的固碳研究表明: *Paramuricea clavata* 固定有机碳速率为 (0.73±0.71) g C m<sup>-2</sup> a<sup>-1</sup>, *Eunicella singularis* 为 (0.73±0.89) g C m<sup>-2</sup> a<sup>-1</sup> 以及 *Leptogorgia sarmentosa* 为 (0.03±0.02) g C m<sup>-2</sup> a<sup>-1</sup>。

微型生物固碳也被认为是非常有潜力的蓝碳固碳方式之一 (Jiao et al., 2014; 唐剑武等, 2018)。海洋中浮游植物是海洋初级生产力的主要贡献者, 年平均生产力占地球表面初级生产力的 46.2% (Field et al., 1998)。浮游植物通过传统的生物泵原理将 CO<sub>2</sub> 逐步转化为在海底能沉降的颗粒有机碳 (POC)。近年来的微型生物碳泵 (MCP) 进一步从微生物和分子生物的机理上阐述微型生物 (主要为原核生物) 在复杂作用下能将溶解有机碳 (DOC)

转化为能长期保存在海洋中的惰性溶解有机碳 (RDOC), 因此有较高的固碳潜力 (Jiao and Zheng, 2011; 焦念志等, 2011, 2013; Jiao et al., 2014)。海洋中巨大的 DOC 库, 即使 MCP 过程只有 5%~7% 转化率, 就能产生类似大气碳库的巨大 RDOC 碳库 (张瑶等, 2017), 而现有推算全球海洋 MCP 对碳循环的贡献达到 0.2 Pg C a<sup>-1</sup> (Legendre et al., 2015)。在营养盐丰富的海岸带生态系统中, 浮游植物和微型生物的丰度和多样性远高于远海, 因此海洋微型生物碳泵的作用更适用于海岸带地区。基于此, 在海岸带地区如何增进微型生物碳泵的功能, 增加海岸带的碳汇, 值得进一步的探索和研究 (唐剑武等, 2018)。

### 3 影响海岸带蓝碳生境及其碳库保存的因素

海岸带蓝碳生境在“增汇”方面发挥着非常重要的作用, 然而自 20 世纪初以来蓝碳生境面积及其蕴藏的碳库已经在快速减少。相关的具体数据更能说明这一危机: 目前全球约 1/3 的蓝色碳汇区域不复存在, 尚存区域也正以 0.7%~7% 的速率快速减少 (Valiela et al., 2001), 其在全球范围内消失速度是热带森林 (每年 0.5%) 的 2~15 倍 (Achard et al., 2002), 并且由于生境消失而造成额外的碳排放达到了 0.15~1.02 Pg C a<sup>-1</sup> (Pendleton et al., 2012)。按生境类型来看, 自 20 世纪 80 年代以来, 全球约 20% 的红树林区域遭受破坏, 当前的消失速度为每年 0.7%~3% (Alongi, 2002), 预测 21 世纪末红树林生境可能全部消失 (Duke et al., 2007), 同时由于红树林破坏而造成额外的碳排放达到 7.0 Tg C a<sup>-1</sup> (Atwood et al., 2017)。自 1800 年以来全球约 25% 的盐沼区域已不复存在, 当前的消失速度为每年 1%~2% (Duarte et al., 2008), 预测 21 世纪末将有 30%~40% 的盐沼湿地将消失 (IPCC, 2007)。全球约 1/3 的海草区域已消失, 20 世纪 70 年代消失速度低于每年 0.9%, 但 2000 年以来消失速度超过了每年 7% (Waycott et al., 2009)。基于此, 亟需相应的管理策略保护和恢复海岸带的蓝色碳汇。不过, 在此之前, 研究影响海岸带蓝碳生境和碳库保存的因素首当其冲。综合前人的研究成果, 自然变化 (包括海平面上升和气候变暖) 和人类活动 (富营养化以及土地利用改变) 是影响蓝碳生境变化和碳库

的储存的常见因素(Spivak et al., 2019)。

### 3.1 自然过程

#### 3.1.1 海平面上升

世界气象组织2022年报告显示:近30年全球平均海平面上升速率约为 $(3.4\pm 0.3)$ mm/a,近10年这一数据增加到了4.4 mm/a(WMO, 2022;图3a)。海平面上升会侵蚀和淹没红树林和盐沼(Silliman et al., 2009),同时由于水深加大导致可见光减少也会阻碍海草床光合作用及其生长发育(Björk et al., 2008)。模型预测表明:到2100年约20%~78%的滨海湿地消失可能与海平面上升有直接关系(Spencer et al., 2016)。海平面上升会影响大量处于高风险脆弱性区域的滨海湿地(图3e),包括印—太平洋滨海地区、美国太平洋和墨西哥海岸地区(Lovelock et al., 2015; Thorne et al., 2018),特别是泥沙输入少且潮差低的地区(Lovelock et al., 2015),或者区域地面压实沉降严重的区域,如密西西比河三角洲海沼沙岭平原(Jankowski et al., 2017)。模拟显示在低沉积物输入( $<2.5\text{ g m}^{-3}$ )且小于1 m潮差的红树林地区,以目前的海平面上升速率(平均约 $(3.2\pm 0.4)$ mm/a)(IPCC, 2013; Canadell and Schulze, 2014),可能在2080年就会被淹没(Lovelock et al., 2015)。

虽然如此,适当的海平面上升也能刺激湿地植被生产力增加(Morris et al., 2012),有机质加积速率变快,并捕获更多泥沙,短期内会增加地表高程(Fagherazzi et al., 2012),同时提高碳埋藏加积速率(McTigue et al., 2019; Rogers et al., 2019a),在一定程度上揭示出滨海湿地对海平面上升的反弹适应性(Kirwan et al., 2016; Wang et al., 2019)。如果向陆一侧有一定的扩展空间,在高海平面上升场景中,滨海湿地的适应性和损失率可能比以往模拟预测低(Kirwan et al., 2016)。Schuerch et al.(2018)综合考虑滨海地形地貌和社会经济影响等情况,模拟发现:以现今的海平面上升速率,到2100年滨海湿地损失率在0~30%;如果考虑37%的区域有向陆地扩展的空间,滨海湿地最高可能有60%的面积增幅(Schuerch et al., 2018)。

#### 3.1.2 气候变化

温度变化是主要气候变化因素,包括大气、土壤和海洋在内的温度变化会较大程度上导致海岸

带蓝碳生境系统产生相应的变化,从而影响固碳能力和碳库储存。气温变化通常影响植被的初级生产力和土壤微生物的分解速率(Spivark et al., 2019)。实验条件下结果显示:气温从0℃变化到30℃,植物光合作用增加4倍,而呼吸作用(分解作用)增加16倍;而模拟显示:平均每增加1℃,高纬度地区湿地光合呼吸作用增温效应是低纬度地区的4倍(Allen et al., 2005; Lopez-Urrutia et al., 2006)。2022年全球年平均气温较工业化前(1850—1900年)高 $(1.15\pm 0.13)$ ℃(WMO, 2022;图3b),变暖的气候对蓝碳保存存在一定的影响。实际上,较高的二氧化碳浓度,更温暖的气温以及适量海平面上升能促进植被初级生产力的提高,从而促使湿地的加积速率增加(Kirwan and Megonigal, 2013)。Kirwan and Mudd(2012)综合模拟互花米草的碳埋藏加积量显示:气温升高在一段时间内(2050年以前)能促进全球互花米草湿地碳埋藏加积速率,但21世纪中后期随着气温继续增加海平面持续上升后会快速下降,同时滨海湿地生境也会大部分消失。

土壤温度增高除了导致微生物分解作用加强外,同时也会导致埋藏的老碳变得更加活跃(Wilson et al., 2016),从而可能会降低滨海湿地土壤有机碳的埋藏。英国酸性水质监测网1988—2000年持续监测显示:在20世纪90年代年平均气温增加0.66℃背景下,河水中溶解有机碳含量年均增加了约5.4%(Freeman et al., 2001)。Freeman et al.(2001)模拟实验显示泥炭沼泽土壤温度增加10℃,苯酚氧化酶活度提高36%,从而导致溶解有机碳也呈等比例的活跃性增加。海水温度增加的结果可能更加直接,会导致蓝碳生境,如海草属种*Posidonia oceanica*的直接消失(Marbà and Duarte, 2010)。Jordà et al.(2012)预测到21世纪中叶由于海水温度上升,地中海地区的海草床将完全消失(图3i)。

除此之外,气候变化易导致滨海湿地地区风暴潮、河/海水泛滥和海水入侵变得更加频繁,会对滨海湿地土壤有机碳埋藏造成一定程度的影响(Wen et al., 2019)。Chambers et al.(2013)实验模拟发现盐度变化造成土壤中微生物呼吸作用发生变化,是土壤有机碳含量发生变化的主要原因,而风暴潮会加速淡水湿地土壤有机碳含量的损失,河流泛滥淡水注入同样会导致盐沼和半咸水湿地中土壤有机

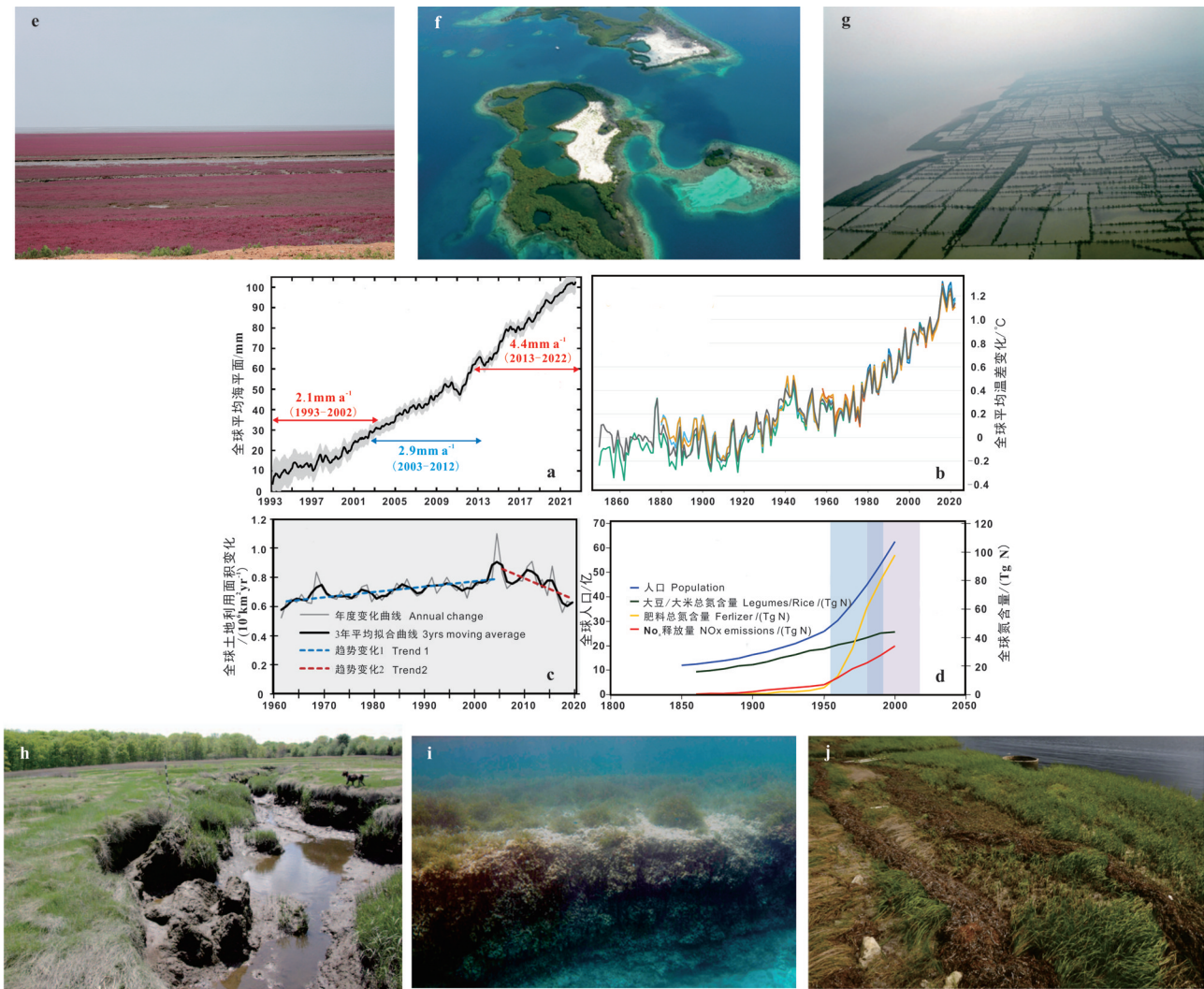


图3 影响海岸带滨海湿地和蓝碳碳库保存的主要因素

a—1993—2022年全球平均海平面变化曲线(据 WMO, 2022 修改),近 30 年平均海平面上升速率约为  $(3.4 \pm 0.3)$  mm,其中 1993—2002 平均海平面上升速率约为  $2.1$  mm,2003—2012 年增加到  $2.9$  mm/a,最近 10 年(2013—2022 年)达到  $4.4$  mm/a;b—1850—2022 年全球平均气温与大规模工业化前(1850—1900 年)平均温差曲线(据 WMO, 2022 修改),2022 年全球平均气温较 1850—1900 年温差约为  $(1.15 \pm 0.13)$  °C;c—全球年平均土地利用变化面积曲线,近 60 年全球年平均土地利用面积变化约为  $72$  万  $\text{km}^2$ ,总体呈现 1960—2004 年逐年上升,2005 年开始快速下降(据 Winkler et al., 2021 修改);d—1800 年以来全球人口数量变化和氮素总量变化曲线,总体显示 1950 年以来全球土壤和海洋中氮含量均呈明显上升趋势(Rabalais et al., 2014);e—未来海平面上升可能会淹没翅碱蓬湿地(红海滩);f—人类建设活动破坏了红树林生境(图片摘自 Kirwan et al., 2013);g—红树林湿地被大量改造成养虾池(图片摘自 Kirwan et al., 2013);h—富营养化使得滨海盐沼湿地更容易遭受侵蚀(图片摘自 Deegan et al., 2012);i—海洋变暖使得海草床生境逐渐萎缩(图片摘自 Fourqurean et al., 2012);j—气候变暖导致风暴潮频次和强度增加,更多冲上岸的凋落物影响湿地植被生长,同时增强了温室气体排放(图片摘自 Macreadie et al., 2013)

Fig. 3 Main factors affecting coastal wetlands and blue carbon storage

a—The global mean sea level change curve from 1993 to 2022 (modified from WMO, 2022) shows that the mean sea level rise rate was about  $(3.4 \pm 0.3)$  mm/a in the last 30 years, which was about  $2.1$  mm/a from 1993 to 2002 and increased to  $2.9$  mm/a in 2003—2012 and  $4.4$  mm/a in the last decade (2013—2022); b—Curves of global annual mean temperature difference from pre-industrial conditions (1850—1900) (modified from WMO, 2022). The global mean temperature difference between 2022 and the 1850—1900 is about  $(1.15 \pm 0.13)$  °C; c—Curves of global average annual land use change area. During the recent 60 years, the area of global average annual land-use change was about  $720000$   $\text{km}^2$ , showing a slightly increasing trend from 1960 to 2004 and a rapid decline after 2005 (modified by Winkler et al., 2021). d—The change curves of global population and total nitrogen since 1800 showed that the global nitrogen content in continents and oceans had an obvious upward trend after 1950 (Rabalais et al., 2014); e—The sea level rise in the future will possibly inundate the coastal wetlands (*Suaeda salsa*); f—Mangrove habitats have been destroyed by human construction activities (image from Kirwan et al., 2013); g—Mangrove wetlands have been extensively transformed into shrimp ponds (image from Kirwan et al., 2013); h—eutrophication makes coastal wetlands more vulnerable to erosion (image from Deegan et al., 2012); i—Ocean warming causes the gradual shrinking of sea grasses habitat (image from Fourqurean et al., 2012); j—Global warming increases the frequency and intensity of storm surges, and more litters are washed ashore, affecting wetland vegetation growth and increasing greenhouse gas emissions (image from Macreadie et al., 2013)



碳损失。同时,风暴潮带来的植物残留体短期内(3—12月内)会造成湿地退化,被掩盖的表层土壤有机碳明显减少。Macreadie et al. (2013)在佛罗里达州圣约翰湾盐沼湿地中调查发现,被植被残留体遮盖的区域表层土壤有机碳比周围有机碳降低了大约30%,意味风暴潮干扰的区域土壤有机碳由原先的净加积变成了净损失(图3j)。

### 3.2 人类活动

#### 3.2.1 土地利用改变

过去近60年的土地利用改变,特别是毁林和农垦活动(图3c),不仅贡献了8%~20%的全球温室气体排放(IPCC, 2007),同时也是滨海湿地大量消亡的主要原因之一:20世纪大约有25%~50%滨海湿地损失主要源自于土地利用改变(Pendleton et al., 2012)。其中,红树林生境因为高利用价值而被大量改造成海产养殖池和水稻田(图3f、3g),是亚洲和南美洲红树林被大量砍伐的重要原因(Valiela et al., 2001; Ahmed and Glaser, 2016)。统计发现1975—2005年亚洲地区有12%的红树林转换成了农田和水产养殖池(Giri et al., 2008)。近来估算显示:毁林农垦造成了全球红树林面积自2000年以来每年以0.39%的速率损失,损失面积达到每年约131~696 km<sup>2</sup> (Hamilton and Casey, 2016),其中损失面积前四的国家分别是印度尼西亚、马来西亚、美国和巴西(Atwood et al., 2017)。由于土地利用改变,中国过去50年损失约73%的红树林和约53%的盐沼湿地(Jiang et al., 2015)。长江三角洲和珠江三角洲地区1990—2015年由于土地利用改变导致滨海湿地面积损失率分别为14.7%(1941 km<sup>2</sup>)和5.3%(335 km<sup>2</sup>)(Lin and Yu, 2018)。

土地利用改变破坏了原始生境类型,导致无法进一步吸收和埋藏蓝碳。Ma et al. (2019)研究发现:黄河三角洲及渤海西南沿岸1970—2010年有将近2028 km<sup>2</sup>的自然湿地转变成了人工经济用地,导致海岸带蓝碳损失率高达10.2%(~1.63 Tg C)(Ma et al., 2019)。另外,损失和破坏的滨海湿地土壤有机碳含量明显下降。Lewis et al. (2019)对澳大利亚南部原生和开垦后盐沼湿地对比分析发现,开垦后的盐沼湿地丢失了近70%的土壤有机质碳(~73 Mg C ha<sup>-1</sup>),并且损失的有机碳部分来自埋藏千年的老碳。丢失这部分碳变成了新的碳源,重新释放到大气中。

Atwood et al. (2017)估算全球红树林因为土地利用改变而造成了每年释放CO<sub>2</sub>达到7~29 Tg C a<sup>-1</sup>。Crooks et al. (2018)估算美国滨海湿地1990—2015年因土地利用改变变成开阔水域,造成每年湿地损失面积为1633~9709 ha a<sup>-1</sup>,年CO<sub>2</sub>释放约为1.26~7.19 Tg C a<sup>-1</sup>;因抽水排干成为旱地,造成每年湿地损失面积为448~1503 ha a<sup>-1</sup>,年CO<sub>2</sub>释放约为0.03~0.11 Tg C a<sup>-1</sup>。

#### 3.2.2 富营养化

自1950年以来全球人口爆炸式增长和含氮磷肥料的大量使用(图3d),使得世界主要河口和海岸带地区水体出现了明显的富营养化状况(Rabalais et al., 2014)。富营养化对滨海湿地不同生境之间发育和固碳可能存在较大的差异。对于生活在海底的海草床而言,富营养化导致浮游的藻类繁盛,导致海草床接受不到足够的阳光(Burkholder et al., 2007),同时藻类分解作用消耗大量的氧气,导致海底缺氧,使得海草床大量死亡(Marbà et al., 2015)。对红树林来说,营养物质通过易分解藻类的繁盛以及水体或土壤中较高碳氮比值等增加促进了红树林土壤层中有机碳的埋藏,但过量营养物质会增加红树林死亡的风险(Lovelock et al., 2009)。

富营养化对滨海盐沼湿地的影响更复杂一些。近来调查发现全球415个重要的富营养化滨海地区中仅13个滨海湿地在恢复中,而欧洲和北美大西洋沿岸的滨海湿地的损失可能部分与富营养化有关(Hartig et al., 2002)。Deegan et al. (2012)对比研究发现:滨海盐沼湿地中在富营养的情况下,潮流河段附近维管植被地下生物量比正常营养条件下的减少了~30%,同时土壤中微生物分解作用加强了~1.9倍,导致河道侵蚀和坍塌加剧,从而阻碍了湿地的自我修复(图3h)。Shifflett 和 Schubauer-Berigan (2019)实验发现:互花米草在轻度富营养化(氮年输入介于0~150 g m<sup>-2</sup>)地面平均生产力能从~500 g C m<sup>-2</sup> a<sup>-1</sup>增加到~1000 g C m<sup>-2</sup> a<sup>-1</sup>,而地下平均生产力则从~5000 g C m<sup>-2</sup> a<sup>-1</sup>急剧降低到~1000 g C m<sup>-2</sup> a<sup>-1</sup>。

#### 3.2.3 其他

泥沙沉积物输入是滨海湿地发育的重要驱动力,因大坝和水库建设导致全球约20%泥沙被截留在上游(Syvitski et al., 2005),减少的泥沙输入量将较大影响海岸带蓝碳生境的稳定性和可持续性

(Kirwan and Temmerman, 2009; Kirwan et al., 2011)。长江三角洲局部滨海湿地区域由于压实作用出现~50 mm/a沉降,但滨海湿地还在继续向海加积,三峡大坝建设后滨海湿地却发育减缓直至停止,如九段沙附近的湿地面积在大坝建设后从原来的加积(2 km<sup>2</sup>/a)变为退积(-1 km<sup>2</sup>/a)(Yang et al., 2006)。印度洋—太平洋区域由于河流筑坝导致入海泥沙减少,约有69%红树林地区地表高程加积速率跟不上海平面上升的速度,蓝碳生境遭受海平面上升的威胁(Lovelock et al., 2015)。

物种入侵,如海平面上升导致原低潮滩的红树林入侵到中高潮滩的盐沼湿地中,或者人工引种的互花米草侵入翅碱蓬湿地,会导致滨海湿地土壤碳库及有机碳埋藏速率发生变化(Yang et al., 2013; Yang et al., 2017)。Bianchi et al.(2013)发现墨西哥湾沿岸红树林侵入到盐沼地中,其固碳效率由101~125 g C m<sup>-2</sup> a<sup>-1</sup>增加到253~270 g C m<sup>-2</sup> a<sup>-1</sup>。不过, Rogers et al.(2019b)对澳大利亚Homebush湾红树林生境、红树林-盐沼混合生境以及盐沼生境17年(2000—2017年)的持续监测发现:虽然红树林生境逐渐侵入盐沼湿地,但原盐沼湿地地表高程、土壤有机碳加积速率并未发生明显变化,暗示入侵红树林生境对碳埋藏和地表高程的提高在最初数十年并不明显,可能需要长期时间积累过程。

海岸侵蚀也对滨海湿地碳埋藏有较大的影响,因为湿地土壤的侵蚀意味着已经保存千年的碳会重新快速释放到大气中,可能会增加现今二氧化碳浓度值。Sapkota and White(2019)调查研究显示密西西比河三角洲Barataria盆地海岸带侵蚀速率49.27~324.85 cm/a,侵蚀深度可到达地面以下1.5 m,由此估算每年由于侵蚀释放到大气中的CO<sub>2</sub>可达到(1.56±0.26)Tg a<sup>-1</sup>。

#### 4 海岸带蓝碳碳库管理策略

近来,澳大利亚学者Peter Macreadie综合全球35位蓝碳科学研究领军专家的观点和意见,在《自然·通讯》上提出未来蓝碳科学研究的10大亟须解决的问题,其中一条便是采用什么管理方法和政策手段来保护和促进蓝碳的封存(Macreadie et al., 2019)。该文认为蓝碳碳库管理应从保护、修复以及创造蓝碳生态系统这三方面入手,而管理策略显然需要综合科学研

究(科学家),政策引导(政策制定者)以及落实执行(直接受益者)三方面的共同努力。

##### 4.1 大力保护已有的蓝碳生态系统

蓝碳生态系统通过高效固碳,可以部分地缓解温室气体急剧增加带来的负面效应(Canadell and Schulze, 2014)。因此,首先保护蓝碳生态系统完整不遭受破坏,不仅可以保存已经埋藏固定下的蓝碳,同时让该生态系统能在未来持续发挥固碳的作用(Macreadie et al., 2019; O'Connor et al., 2020)。

然而,在制定政策之前,对科学家来说,首先要了解蓝碳系统在全球范围或区域尺度内的时空分布情况,并且尽量减少蓝碳总量储量估算中存在的误差(Macreadie et al., 2019)。事实上,因为数据的及时性、可靠性以及不同标准的评价体系,包括红树林在内的蓝碳生态系统,不同学者估算储量大小不尽相同。如关于红树林蓝碳总量,本文引用Hamilton and Freiss(2018)的数据(4.19±0.62) Pg C,而Donato et al.(2011)和Atwood et al.(2017)估算的值分别为4.0~20 Pg C以及~4.4 Pg C。另外,排除在传统蓝碳生态系统之外的海藻(包括巨藻)、海洋贝壳、珊瑚甚至微型生物能否成为新的蓝碳碳库值得进一步讨论(Gao et al., 2016; Krause-Jensen and Duarte, 2016; Macreadie et al., 2019)。Krause-Jensen et al.(2018)因巨藻巨量的初级生产力和蓝碳贡献者角色,将其比作房间内的大象,呼吁蓝碳科学界重视。此外,科学家们还需要继续探究自然条件包括气候变化以及人类活动对蓝碳生态系统以及碳库的影响,以此提出相应的应对对策(Macreadie et al., 2019)。

就政策制定者而言,重要的蓝碳生态系统值得建立类似海洋生态或自然保护区(Howard et al., 2017)。不过,除了考虑面积外,适合的地貌、沉积和水文条件以及社会经济因素也是值得评估的对象。Rogers et al.(2018)认为大盆地流域通常有极好的蓝碳保护区建设条件,而小流域如有良好的湾坝系统也极具潜力。除了保护区建设外,政府层面上的法律法规和政策性文件也必不可少。近几年,中国相继推出了《中共中央国务院关于加快推进生态文明建设的意见》、《“十三五”控制温室气体排放工作方案》、《全国海洋主体功能区划》等多份重要文件中,对发展蓝碳做出了部署(裴理鑫等, 2023)。

另外,蓝碳生态系统的保护可以在碳交易市场和碳汇信用指标等政策方面进行探索(Ullman et al., 2013)。欧盟早在2005年开始探索碳交易(carbon trade)市场(Newell et al., 2012),而中国于2013年也开始了先行试点碳交易。碳交易简单来说,就是碳排放实体通过支付金钱来获得碳排放的额度,而蓝碳交易市场也基于类似的法则。通过获得资金支持,可以更好地保护和修复蓝碳系统。然而目前为止,碳交易市场由于碳储基准、价格波动及国际政治原因,实际运行起来困难重重(林婧,2019)。碳汇信用指标(credit)相当于一个小尺度碳交易市场,直接受益者通过蓝碳保护和修复产生信用点,而相关的机构和单位付钱来购买信用点。该系统类似于REDD+(减少因砍伐森林和森林退化而导致的温室气体排放的计划)。Wylie et al.(2016)以碳汇信用交易介绍了肯尼亚、印度、越南和马达加斯加在蓝碳保护应用方面四个成功案例。类似的市场化信用体系也包括美国的湿地缓解银行(张明祥等,2015)。整体来看,蓝碳生态系统保护的投资回报率是相当可观,潜在利益将远大于投入成本,是一项双赢的举措,理应得到全球协议和碳交易系统的充分重视。

当然,倡导严格保护外,并不意味着完全与开发无关。蓝碳生态系统除了碳库价值外,还有大量的旅游、教育以及渔业资源的价值(Costanza et al., 1997; De Groot et al., 2012; Ye et al., 2016)。其中,生态养殖成为了目前平衡经济发展和生态系统保护一种有效解决方案。Ahmed et al.(2018)综合讨论了红树林有机养殖业,指出过往的红树林养虾池粗放式养殖,通常最多5年因为富营养化和污染等问题就废弃,导致红树林破坏蓝碳碳库损失的同时,也变成了温室气体排放的源。有机生态养殖业要求红树林占比不能小于50%,占据红树林区域养殖的同时需要修复另外50%的红树林面积,类似补偿式的养殖业,形成一种可持续性的发展道路。

#### 4.2 积极开展受损滨海湿地的修复工作

修复已受损的滨海湿地是目前非常热门的话题(Krauss et al., 2017; O'Connor et al., 2020)。类似于保护策略,修复滨海湿地一方面阻止了受损湿地成为温室气体的碳源(减负),另一方面则恢复原蓝碳系统的固碳的能力(增益),同样为双赢之举。

对科学家来说,开展湿地修复示范区的先行工

作,需要提出在哪里修复、如何修复以及后期修复效果评估(Suir et al., 2019)。适合的地貌、沉积和水文条件同样是选择湿地修复区的优先前提(Rogers et al., 2018)。另外,曾经完好而如今退化的滨海湿地也是湿地修复优先选择的区域,不过退化的原因需要调查清楚:自然因素还是人类活动因素占据主动,这对滨海湿地修复至关重要。佛罗里达州沿海地区由于海平面上升,低潮坪红树林大量入侵到中高潮坪的盐沼湿地中(Andres et al., 2019),很显然这是自然因素控制导致原有湿地的退化。人类活动如围海造陆,虾池盐田的开发以及港口码头的建设,目前是中国滨海湿地面积减少和退化的主要原因(Jiang et al., 2015; Cui et al., 2016),因此在人类活动影响导致湿地退化的区域大力开展湿地修复势在必行。

湿地修复需要考虑方面很多,但水文条件的恢复似乎是最直接有效的方式。已有调查的显示发现良好的水文条件似乎比植被结构更影响蓝碳的加积(Fennessy et al., 2019),另外水文条件的连通不仅利于退化湿地植被恢复,也同时加强了蓝碳埋藏并明显降低了温室气体排放。澳大利亚新威尔士围垦湿地在潮流重新连通后,低高程退化湿地减排温室气体由 $264 \text{ g m}^{-2} \text{ a}^{-1} \text{ CO}_2$ 增加到 $351 \text{ g m}^{-2} \text{ a}^{-1} \text{ CO}_2$ (Negandhi et al., 2019),类似的研究情况同样出现在黄河三角洲退化湿地的修复研究中(Zhao et al., 2018)。Kroeger et al.(2019)模拟结果显示潮流连通后土壤有机碳含量明显增加且 $\text{CO}_2$ 净吸收,盐沼湿地排干后土壤有机碳含量明显下降且成为 $\text{CO}_2$ 净排放源,而原盐沼湿地被蓄水拦截或淡化后虽然土壤有机碳变化不大,但可能成为大量 $\text{CH}_4$ 的释放源。

除水文条件恢复外,滨海湿地植被和蓝碳碳库恢复研究也值得重视。全球红树林湿地蓝碳占总量接近一半,然而在东南亚地区养虾池扩张极大破坏了红树林生态系统(Ahmed et al., 2018)。红树林成长速度较慢,其土壤有机碳也同样如此。研究发现,退化红树林土壤有机碳库可能需要15~40年才能恢复到原始的状态(Sasmito et al., 2019),其通常比其他类型滨海湿地(平均7~17年)要慢(O'Connor et al., 2020)。

对于政策制定者和执行者来说,除了出台退渔还湿,退田还湿的政策外,适当开展海岸带湿地修复工程是蓝碳生态系统和碳库保护的一个有力措

施(O'Connor et al., 2020)。Suir et al.(2019)系统总结了密西西比河地区开展滨海湿地修复的情况,发现比起原生湿地( $(415.17\pm 300.1)\text{g C m}^{-2}\text{a}^{-1}$ ),近期修复湿地的碳埋藏速率稍低,为 $(302.29\pm 271.75)\text{g C m}^{-2}\text{a}^{-1}$ ;比起修复植被生态系统,湿地修复蓝碳碳库需要更长的恢复时间,因此湿地修复工程需要投入较长时间金钱和精力。

#### 4.3 创造新的海岸带蓝碳碳库

除了保护和修复传统意义上蓝碳生态系统外,探究新的蓝碳碳库系统也成为科学家们努力的方向。如上文介绍的,海岸带地区海藻、贝壳、珊瑚以及固碳微生物生态系统也是值得关注的方向(Jiao et al., 2014; Gao et al., 2016; Raven, 2018)。在人工海岸开展适合水生植被的护岸,成为“活”的海岸带,也可以创造新的蓝碳碳库增长点(Davis et al., 2015)。

另外,沉积固碳也可以作为海岸带地区,特别是三角洲地区,重要的碳埋藏体和碳库,近年来得到了更多的重视(Dilling et al., 2003; Fujimoto et al., 2009; Shields et al., 2017; Zhao et al., 2019)。在密西西比河三角洲地区,通过工程手段将分流河道改迁至Wax湖,本来一直遭受侵蚀的该地区60年来加积了每平方米3t的沉积物,促进海岸加积的同时,沉积物中土壤中碳累积速率达到了 $(250\pm 23)\text{g C m}^{-2}\text{a}^{-1}$ ,可媲美红树林和盐沼湿地(Shield et al., 2017);Suir et al.(2019)发现通过水文修复的自然湿地碳埋藏速率为 $(240\pm 151)\text{g C m}^{-2}\text{a}^{-1}$ ,而河流分流泥沙供应三角洲沉积物中碳埋藏速率 $(520\pm 490)\text{g C m}^{-2}\text{a}^{-1}$ 。现代黄河三角洲地区1855年以来的三角洲前缘沉积物中碳埋藏速率平均值超过 $500\text{g C m}^{-2}\text{a}^{-1}$ (丁喜桂等, 2014, 2016; Zhao et al., 2015)。以上证据揭示,海岸带地区快速沉积体(三角洲)有潜力成为短期乃至长时间尺度的土壤或沉积物碳库(余雪洋等, 2014; 朱鑫, 2014),因此值得在海岸带地区开展土壤或沉积碳汇方面的地质调查工作(贾黎黎等, 2019; 王诚煜等, 2019; 周攀等, 2022)。

## 5 结 论

本文系统总结海岸带湿地蓝碳的储量和分布情况,并总结了影响海岸带蓝碳生境及其碳库保存的主要因素,提出了海岸带蓝碳碳库管理策略,主要结论如下:

(1)初步估算全球海岸带蓝碳储存总量约为10.8~20 Pg C,平均每年封存碳储约为0.08~0.22 Pg C a<sup>-1</sup>。其中中国蓝碳储量在48.12~123.95 Tg C,平均每年封存碳储约为0.84~1.47 Tg C a<sup>-1</sup>。

(2)自然变化(包括海平面上升和气候变暖)和人类活动(富营养化以及土地利用改变)是影响蓝碳生境变化和碳储的主要原因。

(3)海岸带蓝碳建议从保护、修复以及创造三个维度来开展管理工作,而管理策略的实施需要综合科学研究(科学家),政策引导(政策制定者)以及落实执行(直接受益者)三主体的共同努力。

近年来中国各部门针对海岸带生态系统出台了多项保护措施和政策方针,而针对中国“蓝色碳汇”,学者们也提出许多具体生态工程策略,但对滨海湿地碳汇过程还大多停留在对各生境的定性认识上,缺乏较精确的定量分析、系统研究和宏观评估,亟需统筹开展海岸带蓝碳生境和碳汇调查工作,建立统一的符合国际标准的蓝碳测算标准体系,较精准获取中国蓝碳碳库储量和碳汇封存潜力,同时评估中国蓝碳生境现状和变化原因,提出符合中国国情的蓝碳管理方式,为国家制订相关应对策略与政策提供科学依据,提升中国全球气候治理、碳达峰碳中和、湿地保护等方面的国际综合影响力。

## References

- Achard F, Eva H D, Stibig H J, Mayaux P, Gallego J, Richards T, Malingreau J P. 2002. Determination of deforestation rates of the world's humid tropical forests[J]. *Science*, 297: 999-1002.
- Ahmed N, Bunting S W, Glaser M, Flaherty M S, Diana J S. 2017. Can greening of aquaculture sequester blue carbon?[J]. *Ambio*, 46(4): 468-477.
- Ahmed N, Glaser M. 2016. Coastal aquaculture, mangrove deforestation and blue carbon emissions: Is REDD plus a solution?[J]. *Marine Policy*, 66: 58-66.
- Ahmed N, Thompson S, Glaser M. 2018. Integrated mangrove-shrimp cultivation: Potential for blue carbon sequestration[J]. *Ambio*, 47: 441-452.
- Allen A P, Gillooly J F, Brown J H. 2005. Linking the global carbon cycle to individual metabolism[J]. *Functional Ecology*, 19(2): 202-213.
- Alongi D M. 2002. Present state and future of the world's mangrove forests[J]. *Environmental Conservation*, 29(3): 331-349.
- Alongi D M, Murdiyarto D, Fourqurean J W, Kauffman J B, Wagey T. 2016. Indonesia's blue carbon: A globally significant and

- vulnerable sink for seagrass and mangrove carbon[J]. *Wetlands Ecology & Management*, 24(1): 3–13.
- Andres K, Savarese M, Bovard B, Parsons M. 2019. Coastal wetland geomorphic and vegetative change: Effects of sea-level rise and water management on Brackish Marshes[J]. *Estuaries and Coasts*, 42: 1308–1327.
- Arkema K K, Guannel G, Verutes G, Wood S A, Guerry A, Ruckelshaus M, Kareiva P, Lacayo M, Silver J M. 2013. Coastal habitats shield people and property from sea-level rise and storms[J]. *Nature Climate Change*, 3(10): 913–918.
- Atwood T B, Connolly R M, Almahasheer H, Carnell P E, Duarte C M, Ewers L C J, Irigoien X, Kelleway J J, Lavery P S, Macreadie P I. 2017. Global patterns in mangrove soil carbon stocks and losses[J]. *Nature Climate Change*, 7(7): 523–528.
- Bianchi T S, Allison M A, Zhao Jun, Li Xinxin, Kulawardhana W R. 2013. Historical reconstruction of mangrove expansion in the Gulf of Mexico: Linking climate change with carbon sequestration in coastal wetlands[J]. *Estuarine Coastal & Shelf Science*, 119: 7–16.
- Björk M, Short F, Mcleod E, Beer S. 2008. Managing Seagrasses for Resilience to Climate Change[M]. IUCN, Gland, Switzerland.
- Burkholder J M, Tomasko D A, Touchette B W. 2007. Seagrasses and eutrophication[J]. *Journal of Experimental Marine Biology & Ecology*, 350(1/2): 46–72.
- Canadell J G, Raupach M R. 2008. Managing forests for climate change mitigation[J]. *Science*, 320(5882): 1456–1457.
- Canadell J G, Schulze E D. 2014. Global potential of biospheric carbon management for climate mitigation[J]. *Nature Communications*, 5: 5282.
- Chambers L G, Osborne T Z, Reddy K R. 2013. Effect of salinity-altering pulsing events on soil organic carbon loss along an intertidal wetland gradient: A laboratory experiment[J]. *Biogeochemistry*, 115(1/3): 363–383.
- Chmura G L, Anisfeld S C, Cahoon D R, Lynch J C. 2003. Global carbon sequestration in tidal, saline wetland soils[J]. *Global Biogeochemical Cycles*, 17(4): 1111.
- Coppiari M, Zanella C, Rossi S. 2019. The importance of coastal gorgonians in the blue carbon budget[J]. *Scientific Reports*, 9: 13550.
- Costanza R, d'Arge R, Groot R de, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, Robert V O, Jose P, Robert G R, Paul S, Marjan van den B. 1997. The value of the world's ecosystem services and natural capital[J]. *Nature*, 387(6630): 253–260.
- Couwenberg J, Dommain R, Joosten H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia[J]. *Global Change Biology*, 16(6): 1715–1732.
- Crooks S, Sutton-Grier A E., Troxler T G., Herold N, Bernal B, Schile-Beers L, Wirth T. 2018. Coastal wetland management as a contribution to the US National Greenhouse Gas Inventory[J]. *Nature Climate Change*, 8: 1109–1112.
- Cui Baoshan, He Qiang, Gu Binhe, Bai Junhong, Liu Xinhui. 2016. China's coastal wetlands: Understanding environmental changes and human impacts for management and conservation[J]. *Wetlands*, 16: 737–745.
- Davis J L, A. Currin C, Colleen O, Craig R, Amanda D, Li Bo. 2015. Living shorelines: Coastal resilience with a blue carbon benefit[J]. *Plos One*, 10(11): e0142595.
- De Groot R, Brander L, Sander van der P, Costanza R, Bernard F, Braat L, Christie M, Crossman N, Ghermandi A, Hein L. 2012. Global estimates of the value of ecosystems and their services in monetary units[J]. *Ecosystem Services*, 1(1): 50–61.
- Dean W E, Gorham E. 1998. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands[J]. *Geology*, 26(6): 535–538.
- Deegan L A, Johnson D S, Warren R S, Peterson B J, Fleeger J W, Fagherazzi S, Wollheim Wilfred M. 2012. Coastal eutrophication as a driver of salt marsh loss[J]. *Nature*, 490: 388–392.
- Deng Lei, Shangguan ZhouPing, Wu GaoLin, Chang XiaoFeng. 2017. Effects of grazing exclusion on carbon sequestration in China's grassland[J]. *Earth Science Reviews*, 173: 84–95.
- Dilling L, Doney S C, Edmonds J, Gurney K R, Stokes G. 2003. The role of carbon cycle observations and knowledge in carbon management[J]. *Environment & Resources*, 28: 521–558.
- Ding Xigui, Wang Jisong, Zhao Guangming, Yuan Hongming, Wang Jin, Ye Siyuan. 2016. Accretion rate and controlling factors of carbon and nutrients during coastal wetland evolution in Yellow River Delta[J]. *Geology in China*, 43(1): 319–328 (in Chinese with English abstract).
- Ding Xigui, Ye Siyuan, Zhao Guangming, Yuan Hongming, Wang Jin. 2014. Accumulation of carbon and nutrients in coastal wetland in the Yellow River Delta[J]. *Oceanologia et Limnologia Sinica*, 45(1): 94–102 (in Chinese with English abstract).
- Ding Yihui, Ren Guoyu, Shi Guangyu. 2006. National assessment report of climate change (I): Climate change in China and its future trend[J]. *Advance in Climate Change Research*, 2(1): 3–8 (in Chinese with English abstract).
- Dixon R K, Solomon A M, Brown S, Houghton R A, Trexler M C, Wisniewski J. 1994. Carbon Pools and Flux of Global Forest Ecosystems[J]. *Science*, 263(5144): 185–190.
- Donato D C, Kauffman J B, Murdiyarto D, Kurnianto S, Stidham M, Kanninen M. 2011. Mangroves among the most carbon-rich forests in the tropics[J]. *Nature Geoscience*, 4(5): 293–297.
- Duan Xiaonan, Wang Xiaoke, Yin Tao, Chen Lin. 2006. Advance in studies on carbon sequestration potential of wetland ecosystem[J]. *Ecology and Environment*, 15(5): 1091–1095 (in Chinese with English abstract).
- Duarte C M, Middelburg J, Caraco N. 2005. Major role of marine vegetation on the oceanic carbon cycle[J]. *Biogeosciences*, 2: 1–8.
- Duarte C M. 2009. Coastal eutrophication research: A new

- awareness[J]. *Hydrobiologia*, 629(1): 263–269.
- Duarte C M. 2017. Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget[J]. *Biogeosciences*, 14(2): 301–310.
- Duarte C M, Dennison W C, Orth R J W, Carruthers T J B. 2008. The Charisma of coastal ecosystems: Addressing the imbalance[J]. *Estuaries & Coasts*, 31(2): 233–238.
- Duarte C M, Losada I J, Hendriks I E, Mazarrasa I, Marbà N. 2013. The role of coastal plant communities for climate change mitigation and adaptation[J]. *Nature Climate Change*, 3(11): 961–968.
- Duke N C, Meynecke J O, Dittmann S, Ellison A M, Anger K, Berger U, Cannicci S, Diele K, Ewel K C, Field, C D. 2007. A World Without Mangroves?[J]. *Science*, 317(5834): 41–42.
- Fagherazzi S, Kirwan M L, Mudd S M, Guntenspergen G R, Temmerman S, D'Alpaos A, Van De Koppel J, Rycobyk J M, Reyes E, Craft C. 2012. Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors[J]. *Reviews of Geophysics*, 50(1): RG1002.
- Fennessy M S, Ibanez C, Calvo-Cubero J, Sharpe P, Rovira A, Callaway J, Caiola N. 2019. Environmental controls on carbon sequestration, sediment accretion, and elevation change in the Ebro River Delta: Implications for wetland restoration[J]. *Estuarine Coastal and Shelf Science*, 222: 32–42.
- Field C B., Behrenfeld M J, Randerson J T, Falkowski P. 1998. Primary production of the biosphere: Integrating terrestrial and oceanic components[J]. *Science*, 281(5374): 237–240.
- Fourqurean J W, Duarte C M, Kennedy H, Marbà N, Holmer M, Mateo M A, Apostolaki E T, Kendrick G A, Krause-Jensen D, McGlathery K J. 2012. Seagrass ecosystems as a globally significant carbon stock[J]. *Nature Geoscience*, 5(7): 505–509.
- Freeman C, Evans C D, Monteith D T, Reynolds B, Fenner N. 2001. Export of organic carbon from peat soils[J]. *Nature*, 412(6849): 785.
- Friedlingstein P, O'sullivan M, Jones M W, Andrew R M, Gregor L, Hauck J, Le Quéré C, Luijckx Ingrid T, Olsen A, Peters G P. 2022. Global carbon budget 2022[J]. *Earth System Science Data*, 14(11): 4811–4900.
- Fujimoto K, Kawase K, Ishizuka S, Shichi K, Ohira A, Adachi H. 2009. Sediment and carbon storages in the Yahagi River Delta during the Holocene, central Japan[J]. *Quaternary Science Reviews*, 28(15/16): 1472–1480.
- Gao Yang, Yu Guirui, Yang Tiantian, Jia Yanlong, He Nianpeng, Zhuang Jie. 2016. New insight into global blue carbon estimation under human activity in land-sea interaction area: A case study of China[J]. *Earth Science Reviews*, 159: 36–46.
- Giri C, Ochieng E, Tieszen L L, Zhu Z, Singh A, Loveland T, Masek J, Duke N. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data[J]. *Global Ecology & Biogeography*, 20(1): 154–159.
- Giri C, Zhu Z, Tieszen L L, Singh A, Gillette S, Kelmelis J A. 2008. Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia[J]. *Journal of Biogeography*, 35(3): 519–528.
- Guan Daoming. 2012. *China Coastal Wetlands* (in Chinese) [M]. Beijing: Ocean Press, 233.
- Hamilton S E, Casey D. 2016. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21)[J]. *Global Ecology and Biogeography*, 25(6): 729–738.
- Hamilton S E, Friess D A. 2018. Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012[J]. *Nature Climate Change*, 8(3): 240–244.
- Hartig E K, Gornitz V, Kolker A, Mushacke F, Fallon D. 2002. Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City[J]. *Wetlands*, 22(1): 71–89.
- Howard J, Mcleod E, Thomas S, Eastwood E, Fox M, Wenzel L, Pidgeon E. 2017. The potential to integrate blue carbon into MPA design and management[J]. *Aquatic Conservation Marine & Freshwater Ecosystems*, 27: 100–115.
- IPCC. 2007. *Climate change synthesis report*[C]. Geneva, Switzerland.
- IPCC. 2013. *Climate Change 2013—The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*[M]. Cambridge: Cambridge University Press, 1552.
- IPCC. 2014. *AR5 Climate Change 2014: Mitigation of Climate Change*[C]. Intergovernmental Panel on Climate Change, Copenhagen.
- IPCC. 2018. *Global Warming of 1.5 °C*[C]. Intergovernmental Panel on Climate Change, Incheon.
- Jankowski K L, Törnqvist T E, Fernandes A M. 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise[J]. *Nature Communications*, 8(1): 1–7.
- Jia Lili, Zhu Xin, Zhao Yi, Li Tingting. 2019. Spatial and temporal variation of soil carbon storage and organic carbon content in Leizhou Peninsula, Guangdong Province[J]. *Geology and Mineral Resources of South China*, 35(3): 373–379 (in Chinese with English abstract).
- Jiang Tingting, Pan Jianfen, Pu Xinming, Wang Bo, Pan Jingjin. 2015. Current status of coastal wetlands in China: Degradation, restoration, and future management[J]. *Estuarine, Coastal and Shelf Science*, 164: 265–275.
- Jiao Nianzhi. 2012. Carbon fixation and sequestration in the ocean, with special reference to the microbial carbon pump[J]. *Scientia Sinica Terrae*, (42): 1473–1486 (in Chinese).
- Jiao Nianzhi, Robinson C, Azam F, Thomas H, Baltar F, Dang H, Hardman-Mountford N J, Johnson M, Kirchman D L, Koch B P. 2014. Mechanisms of microbial carbon sequestration in the ocean—future research directions[J]. *Biogeosciences*, 11(19): 5285–5306.

- Jiao Nianzhi, Zhang Chuanlun, Li Chao, Wang Xiaoxue, Dang Hongyue, Zeng Qinglu, Zhang Rui, Zhang Yao, Tang Kai, Zhang Zilian, Xu Dapeng. 2013. Controlling mechanisms and climate effects of microbial carbon pump in the Ocean[J]. *Scientia Sinica Terrae*, 43: 1–18 (in Chinese).
- Jiao Nianzhi, Zheng Qiang. 2011. The microbial carbon pump: From genes to ecosystems[J]. *Applied & Environmental Microbiology*, 77(21): 7439–7444.
- Jiao Nianzhi, Zheng Qiang, Li Yanling, Luo Tingwei, Zhang Yao, Zhang Rui, Tang Kai, Chen Feng, Zeng Yonghui, Zhang Yongyu. 2011. Microbial carbon pump in the ocean—from microbial ecological process to carbon cycle mechanism[J]. *Journal of Xiamen University (Natural Science)*, 50(2): 387–397 (in Chinese).
- Jordà G, Marbà N, Duarte C M. 2012. Mediterranean seagrass vulnerable to regional climate warming[J]. *Nature Climate Change*, 2(11): 821–824.
- Kirwan M L, Temmerman S. 2009. Coastal marsh response to historical and future sea-level acceleration[J]. *Quaternary Science Reviews*, 28(17/18): 1790–1808.
- Kirwan M L, Megonigal J P. 2013. Tidal wetland stability in the face of human impacts and sea-level rise[J]. *Nature*, 504(7478): 53–60.
- Kirwan M L, Mudd S M. 2012. Response of salt-marsh carbon accumulation to climate change[J]. *Nature*, 489(7417): 550–553.
- Kirwan M L, Murray A B, Donnelly J P, Corbett D R. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates[J]. *Geology*, 39(5): 507–510.
- Kirwan M L, Temmerman S, Skeehean E E, Guntenspergen G R, Fagherazzi S. 2016. Overestimation of marsh vulnerability to sea level rise[J]. *Nature Climate Change*, 6: 253–260.
- Krause-Jensen D, Duarte C M. 2016. Substantial role of macroalgae in marine carbon sequestration[J]. *Nature Geoscience*, 9(10): 737–742.
- Krause-Jensen D, Lavery P, Serrano O, Marba N, Masque P, Duarte C M. 2018. Sequestration of macroalgal carbon: the elephant in the Blue Carbon room[J]. *Biology Letters*, 14: 20180236.
- Krauss K W, Cormier N, Osland M J, Kirwan M L, Stagg C L, Nestlerode J A, Russell M J, From A S, Spivak A C, Dantin D D. 2017. Created mangrove wetlands store belowground carbon and surface elevation change enables them to adjust to sea-level rise[J]. *Scientific Reports*, 7(1): 1030.
- Kroeger K D, Crooks S, Moseman-Valtierra S, Tang Jianwu. 2019. Restoring tides to reduce methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention[J]. *Scientific Reports*, 7(1): 11914.
- Lal R. 2004. Soil Carbon sequestration impacts on global climate change and food security[J]. *Science*, 304(5677): 1623–1627.
- Legendre L, Rivkin R B, Weinbauer M G, Guidi L, Uitz Julia. 2015. The microbial carbon pump concept: Potential biogeochemical significance in the globally changing ocean[J]. *Progress in Oceanography*, 134: 432–450.
- Lewis C J E, Baldock J A, Hawke B, Gadd P S, Zawadzki A, Heijnen H, Jacobsen G E, Rogers K, Macreadie P I. 2019. Impacts of land reclamation on tidal marsh "blue carbon" stocks[J]. *Science of The Total Environment*, 629: 427–437.
- Lin Jing. 2019. Theoretical basis and ruling of law to Blue Carbon protection[J]. *China Soft Science*, 10: 14–23 (in Chinese with English abstract).
- Lin Qiaoying, Yu Shen. 2018. Losses of natural coastal wetlands by land conversion and ecological degradation in the urbanizing Chinese coast[J]. *Scientific Reports*, 8: 15046.
- Lo Iacono C, Mateo M A, Gràcia E, Guasch L, Carbonell R, Serrano L, Serrano O, Daobeitia J. 2008. Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): Implications for carbon sink estimates[J]. *Geophysical Research Letters*, 35(18): L18601.
- Lopez-Urrutia A, Martin E S, Harris R P, Irigoien X. 2006. Scaling the metabolic balance of the oceans[J]. *Proceedings of the National Academy of Sciences of the United States of America*, 103(23): 8739–8744.
- Lovelock C E, Ball M C, Martin K C, Feller I C. 2009. Nutrient enrichment increases mortality of mangroves[J]. *Plos One*, 4(5): e5600.
- Lovelock C E, Cahoon D R, Friess D A, Guntenspergen G R, Krauss K W, Reef R, Rogers K, Saunders M L, Sidik F, Swales A. 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise[J]. *Nature*, 526(7574): 559–563.
- Ma Tiantian, Li Xiaowen, Bai Junhong, Ding Shiyuan, Zhou Fangwen, Cui Baoshan. 2019. Four decades' dynamics of coastal blue carbon storage driven by land use/land cover transformation under natural and anthropogenic processes in the Yellow River Delta, China[J]. *Science of The Total Environment*, 655: 741–750.
- Mackey, B G, Keith, H, Berry, S L, Lindenmayer, D B, 2008. Green Carbon: The role of natural forests in carbon storage. Part 1. a green carbon account of australia's south-eastern eucalypt forests, and Policy implications[C]. Canberra: The Australian National University.
- Macreadie P I, Anton A, Raven J A, Beaumont N, Connolly R M, Friess D A, Kelleway J J, Kennedy H, Kuwae T. 2019. The future of Blue Carbon science[J]. *Nature Communications*, 10: 3998.
- Macreadie P I, Randall H A, Kimbro D L. 2013. Loss of "Blue Carbon" from coastal salt marshes following habitat disturbance[J]. *Plos One*, 8(7): e69244.
- Marba N, Arias-Ortiz A, Kendrick G A, Masqué P, Mazarrasa I, Bastyan G R, Garcia-Orellana J, Duarte C M. 2015. Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks[J]. *Journal of Ecology*, 103(2): 296–302.
- Marbà N, Duarte C M. 2010. Mediterranean warming triggers seagrass

- (*Posidonia oceanica*) shoot mortality[J]. *Global Change Biology*, 16(8): 2366–2375.
- McKee K L, Cahoon D R, Feller I C. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation[J]. *Global Ecology & Biogeography*, 16(5): 545–556.
- McLeod E, Chmura G L, Bouillon S, Salm R, Bjork M, Duarte C M, Lovelock C E, Schlesinger W H, Silliman B R. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO<sub>2</sub>[J]. *Frontiers in Ecology & the Environment*, 9(10): 552–560.
- McTigue N, Davis J, Rodriguez A B, McKee B, Atencio A, Currin C. 2019. Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia[J]. *Journal of Geophysical Research: Biogeosciences*, 124: 2945–2957.
- Meng Weiqing, Feagin R A, Hu Beibei, He Mengxuan, Li Hongyuan. 2019. The spatial distribution of blue carbon in the coastal wetlands of China[J]. *Estuarine Coastal and Shelf Science*, 222: 13–20.
- Morris J T, Edwards J, Crooks S, Reyes E. 2012. Assessment of carbon sequestration potential in coastal wetlands[C]//R. Lal (ed.). *Recarbonization of the biosphere: Ecosystems and the global carbon cycle*. Dordrecht: Springer science+ Business media, 517–531.
- Moss R H, Edmonds J A, Hibbard K A, Manning M R, Rose S K, Van V D P, Carter T R, Emori S, Kainuma M, Kram T. 2010. The next generation of scenarios for climate change research and assessment[J]. *Nature*, 463(7282): 747–756.
- Negandhi K, Edwards G, Kelleway J J, Howard D, Safari D, Saintilan N. 2019. Blue carbon potential of coastal wetland restoration varies with inundation and rainfall[J]. *Scientific Reports*, 9: 4368.
- Nellemann C, Corcoran E, Duarte C M. 2009. *Blue carbon: A rapid response assessment*[C]. GRID– Arendal: United Nations Environment Programme.
- Newell R G, Pizer W A, Raimi D. 2012. Carbon markets: Past, Present, and Future[J]. *Social Science Electronic Publishing*, 6(1): 191–215.
- O'Connor J J, Fest B J, Sievers M, Swearer S E. 2020. Impacts of land management practices on blue carbon stocks and greenhouse gas fluxes in coastal ecosystems—A meta-analysis[J]. *Global Change Biology*, 26(3): 1354–1366.
- Ouyang Xiaoguang, Lee S Y. 2014. Updated estimates of carbon accumulation rates in coastal marsh sediments[J]. *Biogeosciences*, 11(18): 5057–5071.
- Pei Lixin, Ye Siyuan, He Lei, Zhao Guangming, Yuan Hongming, Ding Xigui, Pei Shaofeng, Li Xue, Wang Faming, Edward A. Laws. 2023. Wetland resources, development and protection in China and management recommendations[J]. *Geology in China*, 50(2): 459–478(in Chinese with English abstract).
- Pendleton L, Donato D C, Murray B C, Crooks S, Jenkins W A, Siflett S, Craft C, Fourqurean J W, Kauffman J B, Marbà N. 2012. Estimating global “Blue Carbon” emissions from conversion and degradation of vegetated coastal ecosystems[J]. *Plos One*, 7(9): e43542.
- Qin Dahe, Luo Yong, Chen Zhenlin, Ren Jiawen, Shen Yongping. 2007. Latest advances in Climate Change Report: Interpretation of the synthesis report of the IPCC Fourth assessment report[J]. *Advances in Climate Change Research*, 3(6): 311–314 (in Chinese with English abstract).
- Qiu Guanglong, Lin Xingzhu, Li Zongshan, Fan Hangqing, Zhou Haolang, Liu Guohua. 2014. Seagrass ecosystems: Contributions to and mechanisms of carbon sequestration[J]. *Chinese Journal of Applied Ecology*, 25(6): 1825–1832 (in Chinese with English abstract).
- Rabalais N N, Cai Wei–Jun, Carstensen J, Conley D J, Fry B, Hu Xinping, Quinones–Rivera Z, Rosenberg R, Slomp C P, Turner R E. 2014. Eutrophication– driven deoxygenation in the coastal ocean[J]. *Oceanography*, 27(1): 172–183.
- Raven J. 2018. Blue carbon: Past, present and future, with emphasis on macroalgae[J]. *Biology Letters*, 14: 20180336.
- Rogers K, Kelleway J J, Saintilan N, Magonigal J P, Adams J B, Holmquist J, Lu Meng, Schile–Beers L, Zawadzki A, Mazumder D, Woodroffe C D. 2019a. Wetland carbon storage controlled by millennial– scale variation in relative sea– level rise[J]. *Nature*, 567: 91–95.
- Rogers K, Macreadie P I, Kelleway J J, Saintilan N. 2018. Blue carbon in coastal landscapes: A spatial framework for assessment of stocks and additionality[J]. *Sustainability Science*, 18: 1–15.
- Rogers K, Saintilan N, Mazumder D, Kelleway J J. 2019b. Mangrove dynamics and blue carbon sequestration[J]. *Biology Letters*, 15: 20180471.
- Sanderman J, Hengl T, Fiske G, Solvik K, Adame M F, Benson L, Bukoski J J, Carnell P, Cifuentes–Jara M, Donato D. 2018. A global map of mangrove forest soil carbon at 30 m spatial resolution[J]. *Environmental Research Letters*, 13(5): 055002.
- Sapkota Y, White J R. 2019. Marsh edge erosion and associated carbon dynamics in coastal Louisiana: A proxy for future wetland– dominated coastlines world– wide[J]. *Estuarine Coastal and Shelf Science*, 226: 106289.
- Sasmitho S D, Taillardat P, Clendenning J N, Cameron C, Friess D A, Murdiyarto D, Hutley L B. 2019. Effect of land– use and land– cover change on mangrove blue carbon: A systematic review[J]. *Global Change Biology*, 25(12): 4291–4302.
- Schuerch M, Spencer T, temmerman S, Kirwan M L, Wolff C, Lincke D, McOwen C J, Pickering M D, Reef R, Vafeidis A T, Hinkel J, Nicholls R J, Brown S. 2018. Future response of global coastal wetlands to sea–level rise[J]. *Nature*, 561: 231–234.
- Shields M R, Bianchi T S, Mohrig D, Hutchings J A, Kenney W F, Kolker A S, Curtis J H. 2017. Carbon storage in the Mississippi River delta enhanced by environmental engineering[J]. *Nature*



- Geoscience, 10: 846–851.
- Shifflett S D, Schubauer– Berigan J. 2019. Assessing the risk of utilizing tidal coastal wetlands for wastewater management[J]. *Journal of Environmental Management*, 236: 269–279.
- Silliman B R, Grosholz T, Bertness M D. 2009. Human Impacts on Salt Marshes: A Global Perspective[M]. University of California Press, Berkeley, CA.
- Spencer T, Schuerch M, Nicholls R J, Hinkel J, Lincke D, Vafeidis A T, Reef R, McFadden L, Brown S. 2016. Global coastal wetland change under sea–level rise and related stresses: The DIVA wetland change model[J]. *Global and Planetary Change*, 139: 15–30.
- Spivak A C, Sanderman J, Bowen J L, Canuel E A, Hopkinson C S. 2019. Global– change controls on soil– carbon accumulation and loss in coastal vegetated ecosystems[J]. *Nature Geoscience*, 12: 685–692.
- Suir G M, Sasser C E, Delaune R D. 2019. Comparing carbon accumulation in restored and natural wetland soils of coastal Louisiana[J]. *International Journal of Sediment Research*, 34: 600–607.
- Syvitski J P M, Voeroesmarty C J, Kettner A J, Green P. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean[J]. *Science*, 308(5720): 376–380.
- Tang Jianwu, Ye Shufeng, Chen Xuechu, Yang Hualei, Sun Xiaohong, Wang Faming, Wen Quan, Chen Shaobo. 2018. Coastal blue carbon: Concept, study method, and the application to ecological restoration[J]. *Science China Earth Sciences*, 61: 637–646 (in Chinese).
- Thorne K, MacDonald G, Guntenspergen G, Ambrose R, Buffington K, Dugger B, Freeman C, Janousek C, Brown L, Rosencranz J. 2018. US Pacific coastal wetland resilience and vulnerability to sea–level rise[J]. *Science Advances*, 4(2): eaao3270.
- Ullman R, Bilbao– Bastida V, Grimsditch G. 2013. Including blue carbon in climate market mechanisms[J]. *Ocean & Coastal Management*, 83: 15–18.
- Valiela I, Bowen J L, York J K. 2001. Mangrove forests: One of the world's threatened major tropical environments[J]. *Bioscience*, 51 (10): 807–815.
- Wang Chengyu, Li Yuchao, Yu Chengguang, Wang Chenglong, Wang Dapeng. 2019. Temporal and spatial distribution characteristics of soil carbon pool in western coast of Liaoning Province and its influencing factors[J]. *Geological Survey and Research*, 42(3): 208–218 (in Chinese with English abstract).
- Wang Faming, Lu Xiaoliang, Sanders Christian J, Tang Jianwu. 2019. Tidal wetland resilience to sea level rise increases their carbon sequestration capacity in United States[J]. *Nature Communications*, 10: 5434.
- Wang Faming, Zhang Jingfan, Ye Siyuan, Liu Jihua. 2022. Coastal blue carbon ecosystems in China[J]. *China Geology*, 5: 193–194.
- Wang Yao, Guo Chihui, Chen Xijie, Jia Liqiong, Guo Xiaona, Chen Ruishan, Zhang Maosheng, Chen Zeyu, Wang Haodong. 2021. Carbon peak and carbon neutrality in China: Goals, implementation path and prospects[J]. *China Geology*, 4: 720–746.
- Waycott M, Duarte C M, Carruthers T J B, Orth R J, Dennison W C, Olyarnik S, Calladine A, Fourqurean J W, Heck K L, Hughes A R. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems[J]. *Proceedings of the National Academy of Sciences*, 106(30): 12377–12381.
- Wen Yongli, Bernhardt E S., Deng Wenbo, Liu Wenjuan, Yan Junxia, Baruch E M, Bergemann C M. 2019. Salt effects on carbon mineralization in southeastern coastal wetland soils of the United States[J]. *Geoderma*, 339: 31–39.
- Wilson R M, Hopple A M, Tfaily M M, Sebestyen S D, Schadt C W, Pfeifer– Meister L, Medvedeff C, Mcfarlane K J, Kostka J E, Kolton M. 2016. Stability of peatland carbon to rising temperatures[J]. *Nature Communications*, 7: 13723.
- Winkler K, Fuchs R, Rounsevell M, Herold M. 2021. Global land use changes are four times greater than previously estimated[J]. *Nature Communications*, 12(1): 2501.
- WMO. 2022. WMO Provisional State of the Global Climate 2022[C]. Sharm el Sheikh, World Meteorological Organization, 1–26.
- Wylie L, Sutton– Grier A E, Moore A. 2016. Keys to successful blue carbon projects: Lessons learned from global case studies[J]. *Marine Policy*, 65: 76–84.
- Yang S L, Li M, Dai S B, Liu Z, Zhang J, Ding P X. 2006. Drastic decrease in sediment supply from the Yangtze River and its challenge to coastal wetland management[J]. *Geophysical Research Letters*, 33: L06408.
- Yang Wen, Zhao Hui, Chen Xinglong, Yin Shenglai, Cheng Xiaoli, An Shuqing. 2013. Consequences of short– term C4 plant *Spartina alterniflora* invasions for soil organic carbon dynamics in a coastal wetland of Eastern China[J]. *Ecological Engineering*, 61: 50–57.
- Yang Wen, Zhao Hui, Leng Xin, Cheng Xiaoli, An Shuqing. 2017. Soil organic carbon and nitrogen dynamics following *Spartina alterniflora* invasion in a coastal wetland of eastern China[J]. *Catena*, 156: 281–289.
- Ye Siyuan, Laws E A, Costanza R, Brix H. 2016. Ecosystem service value for the common reed wetlands in the Liaohe Delta, Northeast China[J]. *Open Journal of Ecology*, 6(3): 129–137.
- Yu Xueyang, Ye Siyuan, Yuknis N L, Laws E A, Zhao Guangming, Yuan Hongming, Ding Xigui, Wang Jin. 2014. Carbon sequestration along vegetation coverage gradient in the Suaeda salsa marsh from the Liaohe Delta[J]. *Geology in China*, 41(2): 648– 657. (in Chinese with English abstract)
- Yue Dongdong, Wang Lumin. 2012. A preliminary research on the accounting system of carbon sink for marine culture of shellfish in China[J]. *Hunan agricultural sciences*, 15: 120– 122 (in Chinese with English abstract).
- Zhang Haibo, Luo Yongming, Liu Xinghua, Fu Chuancheng. 2015. Current researches and prospects on the coastal blue carbon[J]. *Scientia Sinica Terrestria*, 45: 1641–1648 (in Chinese).

- Zhang Li, Guo Zhihua, Li Zhiyong. 2013. Carbon storage and carbon sink of mangrove wetland: Research progress[J]. Chinese Journal of Applied Ecology, 24(4): 1153–1159 (in Chinese with English abstract).
- Zhang Mingxiang, Bao Daming, Wang Yuyu, Liu Yu. 2015. American experience in conservation and management of coastal wetland in san francisco bay, and its inspiration for China[J]. Wetlands Science & Management, 11(1): 24–28 (in Chinese with English abstract).
- Zhang Yao, Zhao Meixun, Cui Qiu, Pan Wei, Qi Jianguo, Chen Ying, Zhang Yongyu, Gao Kunshan, Pan Jingfeng, Wang Guangyi. 2017. Processes of coastal ecosystem carbon sequestration and approaches for increasing carbon sink[J]. Science China Earth Science, 60: 809–820 (in Chinese).
- Zhao Guangming, Ye Siyuan, Laws E A, He Lei, Yuan Hongming, Ding Xigui, Wang Jin. 2019. Carbon burial records during the last ~40,000 years in sediments of the liaohe delta wetland, China[J]. Estuarine Coastal and Shelf Science, 226: 106291.
- Zhao Guangming, Ye Siyuan, Li Guangxue, Ding Xigui, Yuan Hongming. 2015. Late quaternary strata and carbon burial records in the Yellow River delta, China[J]. Journal of Ocean University of China, 14 (3): 446–456.
- Zhao Qingqing, Bai Junhong, Zhang Guangliang, Jia Jia, Wang Wei, Wang Xin. 2018. Effects of water and salinity regulation measures on soil carbon sequestration in coastal wetlands of the Yellow River delta[J]. Geoderma, 319: 219–229.
- Zhou Pan, Ye Siyuan, Wang Jing, Yu Changbin, Yuan Hongming, Pei Lixin, Ding Xigui, Yang Juan, Hans Brix. 2022. Glomalin-related soil protein distribution and its relation to mineral weathering in the wetlands along the Bohai Sea, China[J]. Geology in China, 49(4): 1075–1087(in Chinese with English abstract).
- Zhu Xin. 2014. Temporal and spatial variation of organic carbon and soil carbon storage in the Pearl River Delta economic zone[J]. Geology and Mineral Resources of South China, 30(2): 176–185 (in Chinese with English abstract).
- 附中文参考文献**
- 丁喜桂, 叶思源, 赵广明, 袁红明, 王锦. 2014. 黄河三角洲滨海湿地演化及其对碳与营养成分的扣留[J]. 海洋与湖沼, 45(1): 94–102.
- 丁喜桂, 王吉松, 赵广明, 袁红明, 王锦. 2016. 黄河三角洲滨海湿地演化过程中的碳埋藏效率及其控制[J]. 中国地质, 43(1): 319–328.
- 丁一汇, 任国玉, 石广玉. 2006. 气候变化国家评估报告(I): 中国气候变化的历史和未来趋势[J]. 气候变化研究进展, 3(s1): 1–5.
- 段晓男, 王效科, 尹翌, 陈琳. 2006. 湿地生态系统固碳潜力研究进展[J]. 生态环境学报, 15(5): 201–205.
- 关道明. 2012. 中国滨海湿地[M]. 北京: 海洋出版社, 233.
- 贾黎黎, 朱鑫, 赵艺, 李婷婷. 2019. 雷州半岛土壤碳储量及其有机碳时空变化规律[J]. 华南地质与矿产, 35(3): 373–379.
- 焦念志. 2012. 海洋固碳与储碳—并论微生物在其中的重要作用[J]. 中国科学: 地球科学, 42(10): 1473–1486.
- 焦念志, 张传伦, 李超, 王晓雪, 党宏月, 曾庆璐, 张锐, 张瑶, 汤凯, 张子莲, 徐大鹏. 2013. 海洋微生物碳泵储碳机制及气候效应[J]. 中国科学: 地球科学, 43: 1–18.
- 焦念志, 郑强, 李彦玲, 骆庭伟, 张瑶, 张锐, 汤凯, 陈峰, 曾永辉, 张永雨. 2011. 海洋微生物碳泵—从微生物生态过程到碳循环机制效应[J]. 厦门大学学报(自然科学版), 50(2): 387–401.
- 林婧. 2019. 蓝碳保护的理论与法治进路[J]. 中国软科学, 10: 14–23.
- 裴理鑫, 叶思源, 何磊, 赵广明, 袁红明, 丁喜桂, 裴绍峰, 李雪, 王法明, Edward A. Laws. 2023. 中国湿地资源与开发保护现状及其管理建议[J]. 中国地质, 50(2): 459–478.
- 秦大河, 罗勇, 陈振林, 任贾文, 沈永平. 2007. 气候变化科学的最新进展: IPCC第四次评估综合报告解析[J]. 气候变化研究进展, 3(6): 311–314.
- 邱广龙, 林幸助, 李宗善, 范航清, 周浩郎, 刘国华. 2014. 海草生态系统的固碳机理及贡献[J]. 应用生态学报, 25(6): 1825–1832.
- 唐剑武, 叶属峰, 陈雪初, 杨华蕾, 孙晓红, 王法明, 温泉, 陈少波. 2018. 海岸带蓝碳的科学概念、研究方法以及在生态恢复中的应用[J]. 中国科学: 地球科学, 48(6): 661–670.
- 王诚煜, 李玉超, 于成广, 王成龙, 王大鹏. 2019. 辽宁西部沿海地区土壤碳库时空分布特征及其影响因素[J]. 地质调查与研究, 42(3): 208–218.
- 余雪洋, 叶思源, Nicholas Lawrence Yuknis, Edward A Laws, 赵广明, 袁红明, 丁喜桂, 王锦. 2014. 辽河三角洲翅碱蓬湿地不同植被覆盖度下的土壤对碳的扣留[J]. 中国地质, 41(2): 648–657.
- 岳冬冬, 王鲁民. 2012. 中国海水贝类养殖碳汇核算体系初探[J]. 湖南农业科学, 15: 120–122.
- 张莉, 郭志华, 李志勇. 2013. 红树林湿地碳储量及碳汇研究进展[J]. 应用生态学报, 24(4): 1153–1159.
- 张明祥, 鲍达明, 王玉玉, 刘宇. 2015. 美国旧金山湾滨海湿地保护与管理的经验及启示[J]. 湿地科学与管理, 11(1): 25–28.
- 张瑶, 赵美训, 崔球, 樊炜, 齐家国, 陈鹰, 张永雨, 高坤山, 樊景凤, 汪光义. 2017. 近海生态系统碳汇过程、调控机制及增汇模式[J]. 中国科学: 地球科学, 47(4): 438–449.
- 章海波, 骆永明, 刘兴华, 付传城. 2015. 海岸带蓝碳研究及其展望[J]. 中国科学: 地球科学, 45(11): 1641–1648.
- 郑凤英, 邱广龙, 范航清, 张伟. 2013. 中国海草的多样性、分布及保护[J]. 生物多样性, 21(5): 517–526.
- 周攀, 叶思源, 王锦, 于长斌, 袁红明, 裴理鑫, 丁喜桂, 杨娟, HANS Brix. 2022. 环渤海湿地沉积物球囊霉素相关土壤蛋白分布特征及其对湿地土壤风化的影响[J]. 中国地质, 49(4): 1075–1087.
- 朱鑫. 2014. 珠江三角洲经济区土壤碳储量及有机碳时空变化规律研究[J]. 华南地质与矿产, 30(2): 176–185.