海草床沉积物储碳机制及其对富营养化的响应

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摘要 海草床是近岸海域生产力极高的生态系统, 具有重要的储碳功能, 其碳主要存储于沉积物中. 海草床沉积物有机碳(sediment organic carbon, SOC)储量受其来源、组成和转化的共同影响, 同时, 近岸海域的富营养化会影响到SOC的储存. 通过综述海草床SOC的来源、组成、转化、存储及其对富营养化响应等方面内容, 总结其储碳研究进展. 研究表明, 海草床SOC来源多样, 主要来源为海草和悬浮颗粒物; SOC形态组成主要包括活性有机碳和惰性有机碳, 海草床沉积物中微生物活性较高, 对SOC具有较高的利用效率; 海草床沉积物碳储量呈现显著的地理差异和海草种类差异; 富营养化会导致海草床藻类来源的SOC增加, 从而提高SOC中活性组分, 促进微生物的活性, 加快SOC的利用与转化; 从而影响海草床SOC存储. 最后提出未来海草床沉积物储碳的重点研究方向: (1) 开展海草床储碳量的全球普查; (2) 加强环境变化对海草床沉积物储碳机制的影响研究; (3) 发展海草床碳汇扩增技术; (4) 开发惰性有机碳的研究方法. 我国也应加强海草床储碳相关研究, 并为我国未来的气候谈判和CO₂交易提供科学依据.

关键词 海草床, 沉积物有机碳, 储碳, 富营养化, 响应

海草床生态系统是近岸海域生产力极高的生态系统^[1], 具有重要的生态服务功能, 如育幼^[2]、稳定底质^[3]、降低人类及水生动物患病风险^[4]、污染物质净化和有机碳储存等^[5,6]. 近年来, 随着全球CO₂浓度的升高, 全球变暖成为重大的环境问题, 沿岸生态系统的“蓝碳”逐渐受到重视^[7,8], 其中海草床生态系统是“蓝碳”的重要组成^[9,10]. 海草床的有机碳大部分存储于沉积物中^[9,11], 全球的沉积物存储量估计高达19.9 Pg^[9]. 尽管海草床生态系统占海洋面积的比例不足0.2%, 但每年为海洋有机碳埋藏的贡献高达10%^[9]. 据保守估计, 全球海草床沉积物有机碳(sediment organic carbon, SOC)年际埋藏速率为27.4

Tg C a⁻¹^[12].

近年来, 关于海草床沉积物有机碳存储功能的研究逐渐增多^[10,11,13~16]. 研究表明, 海草床SOC的存储量受到其来源、组成和转化的影响^[15]. 特别是由于人类活动和全球气候变化的影响, 全球海草床面积以每年接近5%的速度消失^[17]. 富营养化是全球海草床退化主要原因之一^[18,19]. 其会改变海草床沉积物碳储功能, 甚至使海草床生态系统由碳汇向碳源转变^[7,13,20].

根据联合国政府间气候变化专门委员会(Intergovernmental Panel on Climate Change, IPCC)估计, 到2050年全球CO₂的排放要比2000年的减少85%, 才

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能防止全球平均气温上升超过 2°C ^[21]. 因此, 研究海草床沉积物储碳, 可为全球碳汇研究提供基础. 本文从海草床SOC的来源、组成、转化、存储及其对富营养化的响应等方面的研究进行总结, 为促进我国海草床沉积物储碳机制研究提供借鉴, 并为我国未来的气候谈判和 CO_2 交易提供科技支撑.

1 海草床沉积物有机碳来源

海草床SOC来源是影响SOC生物可利用性和稳定性的主要因素^[22]. 海草床SOC来源多样, 主要包括海草、附生藻类、大型藻类、浮游植物和底栖微藻等初级生产者^[23,24], 陆源有机物^[16,23]等邻近的生态系统(红树林和盐沼等)^[13,24]输入的碳也可能是海草床SOC的重要来源, 这与海草叶片形成的冠层能促进海草床生态系统对水体中颗粒有机碳的捕捉密切相关^[25,26].

目前, 研究海草床SOC来源的主要方法包括沉积物碳氮比(C/N)、有机碳稳定同位素($\delta^{13}\text{C}$)及生物标志物(如类脂化合物和木质素)等^[13,16,23,24,27~33], 并通过三元混合图解法^[34]、线性混合模型^[24,35]或贝叶斯模型^[36]来计算各来源的所占比例. 一般来说, 陆源有机质的C/N>12, 而海源的为6~9^[37]; 陆源有机碳的 $\delta^{13}\text{C}$ (-28‰~-25‰)大多比海源偏贫(-19‰~-12‰)^[38]. 全球海草床SOC及其可能来源的 $\delta^{13}\text{C}$ 值的汇总见表S1. 分析表明, 各海源初级生产者的 $\delta^{13}\text{C}$ 差异显著, 海草的 $\delta^{13}\text{C}$ 的平均值为-10.1‰, 大型藻类、附生藻类和底栖微藻等藻类的 $\delta^{13}\text{C}$ 平均值约为-15.4‰, 而浮游植物(多以悬浮颗粒物代表, suspended particulate organic matter, SPOM)、红树林及陆源有机物比它们更贫, 平均值分别为-19.3‰, -28.1‰和-27.8‰. 另外, 不同的初级生产者的生物标志物差异显著. 例如, 代表底栖微藻类的生物标志物为多不饱和磷脂脂肪酸(如20:5 ω 3)^[39], 而22:0正构醇^[27]和木质素衍生的芳构化合物^[33]多为海草来源的生物标志物.

Kennedy等人^[28]利用线性混合模型估算全球海草床SOC的来源, 其中来自海草的接近50%. 海草床SOC来源受地理环境影响显著. 例如, Miyajima等人^[16]在东亚和东南亚的海草床研究发现, 温带、亚热带和热带海草床SOC中的海草来源所占比例都不同, 分别为10%~40%, 35%~82%和4%~34%. 地中海沿岸Fanals区域大洋波喜荡草(*Posidonia oceanica*)SOC的海草和SPOM来源比例分别为28%和72%^[40], 而邻近

区域和岛屿的大洋波喜荡草海草床SOC的海草来源约占40%~50%^[29]. 这表明, 不同区域的同一种海草, SOC来源差异也较大. 另外, 同一区域不同海草的SOC来源近似^[24,41], 如海南新村湾海草床, 两种海草优势种泰来草(*Thalassia hemprichii*)和海菖蒲(*Enhalus acodoides*)的SOC的来源比例相近^[41].

2 海草床沉积物有机碳的组成

根据对全球51个海草床区域的SOC含量汇总(图1), 全球海草床SOC的平均含量为1.5%, 其中约70%的海草床SOC含量小于1.5%. 温带和热带海草床SOC含量差异显著(Student's *t*检验, $P<0.05$), 分别为2.00%和0.95%, 这可能与温度上升促进SOC矿化分解有关^[42]. 根据矿化速率的不同将海草床SOC主要分为活性和惰性有机碳库^[22](图2). 活性有机碳(labile organic carbon, LOC)是SOC中活性最高的一部分碳, 并对SOC来源的变化响应迅速, 是SOC活性程度的重要指示^[43]. 微生物量碳(microbial biomass carbon, MBC)和溶解有机碳(dissolved organic carbon, DOC)是LOC库的重要组成^[41,42,44]. 惰性有机碳是指能够长期存在于SOC库的部分, 它代表了SOC库的稳定性^[6,10]. 对比目前有限的海草床沉积物LOC的研究结果, DOC和MBC在不同区域的差异都较大^[22,41,45]. 例如, 中国海南新村湾DOC和MBC的含量分别为212.16~291.92和57.33~694.41 mg kg^{-1} , 平均值分别约占海草床SOC的24%和16%^[41]; 但在佛罗里达海湾(Florida Bay)的海草床却分别约为24~62和1000~2500 mg kg^{-1} , 分别占SOC的<1%和17%~20%^[22]. 海草移植会影响SOC的组成, 如移植1年后的海草床SOC和DOC含量

图1 温带和热带海草床SOC含量的出现频率

Figure 1 Frequency distribution of reported observations of SOC from temperate and tropical seagrass beds

图2 海草床沉积物有机碳的主要组成示意图. 该图改编自Hicks^[22]

Figure 2 The main composition of sediment organic carbon in seagrass beds. This figure originated from Hicks^[22] with some modifications

与未退化海草床区域相近,但MBC在SOC的组成比例(MBC/SOC)仍比未退化海草床区域高,移植后的海草床与未退化海草床中的MBC/SOC分别为24%~38%和17%~20%^[22].海草植株的地下生物量(根和地下茎)约占50%,由于其具有较高C:N:P比值,生物可利用性低^[46,47],成为海草床沉积物惰性有机碳库的重要来源.

3 海草床沉积物有机碳的转化

沉积物微生物的活动对SOC转化过程起到关键作用,其主要驱动因素为底栖细菌^[48].海草床沉积物的细菌大多为硫酸盐还原或硫化物氧化细菌类型^[49,50],其沉积物中细菌活性显著高于邻近无海草区域^[51~54].例如,龟裂泰来草(*Thalassia testudinum*)海草床沉积物的硫酸盐还原效率是邻近无海草沉积物的3~5倍^[52].海草床沉积物中海草碎屑的输入,以及海草根部分释放出的氨基酸、易降解糖类活性有机物质和氧气是底栖微生物高活性的重要原因^[51,55~57].例如, Hansen

等人^[54]估算一种鳎草(*Zostera capricorni*)光合作用固定的碳,其中8%~18%通过根茎释放进入了沉积物;并且海草床沉积物间隙水中DOC的含量是邻近裸地的2~3倍^[58].除直接通过硫酸盐还原作用转化外,沉积物中微生物释放的胞外酶对SOC降解也是其转化的重要途径^[59].沉积物中氧化还原酶(多酚氧化酶和过氧化物酶等)和水解酶(蔗糖酶、 β -葡萄糖苷酶和淀粉酶等)是SOC矿化的重要酶^[60~62].刘松林等人^[61]研究发现,海草床沉积物多酚氧化酶、过氧化物酶、蔗糖酶和纤维素酶活性的平均值分别为 $0.17 \text{ mg g}^{-1} (2 \text{ h})^{-1}$, $0.36 \text{ mg g}^{-1} (2 \text{ h})^{-1}$, $0.43 \text{ mg g}^{-1} (24 \text{ h})^{-1}$ 和 $0.19 \text{ mg g}^{-1} (72 \text{ h})^{-1}$,并比其他类型滨海湿地沉积物的酶活性低,这表明海草床SOC转化速率低.另外,底栖动物对海草床SOC的转化也不容忽视,除通过挖掘、钻洞等扰动促进SOC的氧化外^[63],某些底栖动物还能直接利用SOC,如鳎草(*Zostera marina*)海草床沉积物中的一种钩虾(*Gammarus mucronatus*),可直接通过摄食利用SOC中的藻源碳^[64].

海草的生物量也会影响SOC的转化,这主要是由于海草生物量越高,根茎向沉积物释放的活性有机物质越多,沉积物微生物活性也越高^[51,52].海草床SOC来源组成的变化会改变沉积物微生物有机碳来源,从而影响微生物对SOC转化^[45,65].另外,细菌的活性一般随着沉积物深度的增加而不断的降低^[66],从而减弱了对海草床SOC的利用,这在一定程度上促进了SOC的存储.

4 海草床沉积物有机碳的存储

海草床SOC的储存是其“蓝碳”功能的重要体现^[9,15,67].海草床产生的大量纤维和木质素类物质(根和根茎)能够形成数米甚至十几米的海草碎屑层,并能完整保存几千年^[9,46].例如,位于西班牙Portlligat的大洋波喜荡草海草床沉积物中形成了11.7 m厚的有机碎屑物层,其平均面积的碳储量高达0.18 t C m⁻²^[68];Mateo等人^[46]发现大洋波喜荡草埋存于沉积物中的有机物形态在经历了上千年后几乎没有发生变化.对全球30种海草的生产力数据汇总表明,海草平均初级生产量为1012 g DM m⁻² d⁻¹,高于生物圈其

他大部分类型生态系统^[1];Agawin和Duarte^[25]研究表明,海草草冠可在1 h内捕获进入草冠内73%的悬浮颗粒物,其颗粒物沉降速率是邻近裸地区域的4倍;海草床沉积物的缺氧环境^[28]和海草组织低N和P含量^[69]等都是海草床沉积物较低分解速率的重要因素.因此,海草床高初级生产力、高捕获沉降水体颗粒物能力及沉积物中低分解速率^[10,70]是其储存有机碳能力较高的主要原因.

目前估算海草床SOC的埋藏速率主要利用¹⁴C和²¹⁰Pb,沉积物收集器或通过对海草床年际生产力的调查等方法.沉积物收集器估算的有机碳埋藏速率显著高于其他方法,这是因为该方法在估算短期的沉降量时未考虑有机碳被微生物的利用.全球海草床SOC的埋藏速率研究的总结见表1.在同样的区域用不同的方法会呈现不同的结果,如在西北地中海Medes区域的大洋波喜荡草海草床,利用年际生产力和¹⁴C计算的有机碳埋藏速率分别为72.5和12.6 g C m⁻² a⁻¹^[6,46].根据表1统计,西北地中海区域、澳大利亚、北美地区和东亚及东南亚地区,其有机碳埋藏速率的平均值分别为41, 6.35, 89.3和4.9 g C m⁻² a⁻¹,区域差异显著.

表 1 全球海草床沉积物有机碳埋藏速率

Table 1 Summary of estimates of sediment organic carbon burial rate in seagrass meadows

研究区域		主要海草种类	有机碳埋藏速率 (g C m ⁻² a ⁻¹)	研究方法	参考文献
西班牙	Culip	<i>Posidonia oceanica</i>	9	¹⁴ C	[46]
	Port Lligat	<i>P. oceanica</i>	75	¹⁴ C	[46]
	Medes	<i>P. oceanica</i>	72.5, 12.6	年度碳收支, ¹⁴ C	[6,46]
	Campello	<i>P. oceanica</i>	112.1	¹⁴ C	[46]
	Tabarca	<i>P. oceanica</i>	83	¹⁴ C	[46]
	Balearic Islands	<i>P. oceanica</i>	112.9	¹⁴ C	[71]
	Fanals	<i>P. oceanica</i>	198	沉积物收集器	[40]
	Bay of Calvi	<i>P. oceanica</i>	16.6	年度碳收支	[6]
	Ischia	<i>P. oceanica</i>	19.5, 30.0	年度碳收支, ¹⁴ C	[6,46]
澳大利亚	Cockburn Sound	<i>Posidonia sinuosa</i>	6.35	¹⁴ C	[71]
	Green Island	<i>Thalassia hemprichii</i> , <i>Cymodocea rotundata</i> 和 <i>Halodule uninervis</i>	720~7260	沉积物收集器	[72]
美国	Indian River Lagoon	<i>Syringodium filiforme</i> , <i>Thalassia testudinum</i> , <i>Halodule beaudettei</i> 和 <i>Halophila johnsonii</i>	195	年度碳收支	[22]
墨西哥	Celestun Lagoon	<i>Halodule wrightii</i> 和 <i>Ruppia</i> spp.	40	²¹⁰ Pb	[36]
	Terminos Lagoon	<i>T. testudinum</i>	33	²¹⁰ Pb	[36]
日本	Seto Inland Sea	<i>Zostera marina</i>	6.8	¹⁴ C	[16]
	Ishigaki Island	<i>Enhalus acoroides</i>	5.4	¹⁴ C	[16]
泰国	Andaman Sea	<i>E. acoroides</i> 和 <i>T. hemprichii</i>	2.4	¹⁴ C	[16]

Fourqurean等人^[9]利用地中海、莎克湾(Shark Bay)和佛罗里达海湾海草床的碳库数据估算全球海草床SOC存储的平均值为329.5 Mg C ha⁻¹(1 ha=10000 m²),但Miyajima等人^[16]和Lavery等人^[11]却发现东亚、东南亚区域和澳大利亚海草床SOC的存储量仅为全球估算值的1/4。因此,全球不同区域海草床SOC存储差异显著。另外,海草种类会影响其沉积物碳储量^[11,73]。如Lavery等人^[11]对比澳大利亚沿岸不同种类海草床碳储量的研究发现,存储量呈现一种波喜荡草(*Posidonia sinuosa*)>卵叶喜盐草(*Halophila ovalis*)和一种鳗草(*Zostera muelleri*)>齿叶丝粉草(*Cymodocea serrulata*)和单脉二药草(*Halodule uninervis*)>圆叶丝粉草(*Cymodocea rotundata*)、泰来草(*Thalassia hemprichii*)和大洋波喜荡草等,这可能是由于不同海草的细胞壁和其他保护性物质的生化组成不同^[74],以及不同海草的形态对悬浮颗粒物的捕获能力不同所造成的^[25,75]。即使相同的海草种类,不同地区亦有较大差异,位于西班牙沿岸的巴利阿里群岛(Balearic Islands)和Culip的大洋波喜荡草,其碳埋存率分别为112.9和9 g C m⁻² a⁻¹^[46]。环境因素如分布深度^[11,71]和小尺度空间构型^[31]等也会影响海草床存储量大小。2 m水深的大洋波喜荡草海草床的储碳量是32 m水深的大洋波喜荡草海草床的14~16倍^[71];海草床中心区域的SOC存储量比其边缘区域的高20%^[31]。

5 海草床沉积物有机碳对富营养化的响应

富营养化引起海草床浮游植物、附生藻类和大型藻类的爆发,造成海草的光限制,从而导致海草床的退化^[19]。Schmidt等人^[76]在加拿大东南部沿岸区域研究发现,在高营养盐负荷区域的浮游植物、一种丝藻(*Ulothrix speciosa*)和石莼(*Ulva lactuca*)的生物量分别是低营养盐区域的1.8、40和670倍,但海草茎枝密度、地上和地下生物量在高营养盐区域都呈现显著下降($P<0.05$)。富营养化条件下,海草床生态系统藻类的迅速生长和海草的衰退改变了初级生产者的群落结构^[76~78],进而改变SOC的来源^[13,41]。例如,Macreadie等人^[13]研究发现,自20世纪50年代后,富营养化导致悉尼植物湾(Botany Bay)的SOC来源由海草、红树林等高等植物向底栖微藻类转变;同样,富营养化导致海南新村湾海草床SOC大型藻类和附生藻类的来源平均贡献上升了16%^[41]。由于底栖微藻(6%)、浮游植物(3.9%)和大型藻类的(0.4%)的有机碳埋藏率

都显著低于海草(15.9%)^[47],富营养化可能会削弱海草床的碳汇能力。

相比于海草,大型藻类、附生藻类和浮游植物具有较低的C:N:P比值,更容易被微生物利用^[79]。富营养化导致SOC中藻类的贡献增加,这意味着更多LOC的输入。相关研究表明,将海草和大型藻类的凋落物分别埋于沉积物,在24周的培养时间内,海草凋落物的有机碳减少了48%,但大型藻类凋落物的有机碳减少却高达87%,并且培养大型藻类凋落物的沉积物DOC和总CO₂含量相对较高,分别为437和135 μmol C cm⁻³^[80];Liu等人^[41]在海南新村湾海草床研究发现,富营养化导致藻类贡献上升,沉积物MBC的含量提高了5~7倍。另外,由于SOC藻类贡献的增加会使细菌有机碳的来源向藻类转变,这会提高微生物硫酸盐还原效率,进而促进SOC的矿化^[39]。同时,营养盐增加还会直接提高细菌的活性和生物量,加快SOC的转化。例如,López等人^[81]研究发现,添加营养物质提高了海草床沉积物细菌和胞外酶的活性,使沉积物中的有机物质下降了33%。海草床沉积物中多酚氧化酶、过氧化物酶、蔗糖酶和纤维素酶的活性随着营养负荷的增加而逐渐上升,会加快SOC分解^[61,62]。

富营养化会导致海草生物量下降^[41,76,77,82]。如随着营养盐负荷的上升,海南新村湾海草床的地上生物量下降了约40%^[82];同样,加拿大爱德华王子岛(Prince Edward Island)海草床的地下生物量在高营养盐区域下降了82%^[76]。另外,海草地上生物量的下降还会导致其捕获水体有机碳的能力下降^[40,83],可直接减少海草床SOC的存储。另外,海草床的退化还会导致沉积物已存储有机碳的逃逸和释放^[9,20,84],Marbà等人^[20]在澳大利亚牡蛎港(Oyster Harbour)研究发现,在海草床退化的30年后,不仅导致其储碳能力的消失,还导致退化前海草床存储的SOC逃逸释放;Pendleton等人^[84]估计不同的扰动类型会造成不同程度的有机碳损失,矿化的有机碳比例为25%~100%,海草床生态系统的碳逃逸可造成每年19~137(平均61)亿美元的经济损失。然而,也有研究发现富营养化对海草床SOC的存储没有影响或起促进作用^[14,78]。例如,Howard等人^[78]通过30年的研究发现,富营养化对美国佛罗里达海湾海草床SOC存储无影响;同样在佛罗里达海湾,Armitage和Fourqurean^[14]却发现,短期的富营养化会减少SOC存储,但长期的富营养

化会增加SOC存储。这可能因为SOC对营养负荷响应的非线性和滞后性特征,或是不同生态系统的营养负荷阈值不一致,导致海草床SOC对营养负荷产生了不一样的响应。

6 研究展望

由以上分析可知,尽管已经对海草床沉积物储碳进行了较多的研究,但仍然存在一些不足。结合目前国外学者研究的热点,提出未来海草床沉积物碳储研究的方向:

(1) 开展海草床储碳量的全球普查。全球海草床SOC的存储具有显著的地理差异,并且我国关于海草床碳储存的研究基本尚未开展。因此,加强海草床碳储量的全球普查,尤其是尽快开展我国海草床“蓝碳”的普查与估算,对于更准确估算全球海草床碳储量具有重要意义。

(2) 加强环境变化对海草床沉积物储碳机制影响的研究。探究环境变化(如富营养化、全球变暖和海平面上升等)对海草SOC碳储机制的影响,为维护海草床“蓝碳”功能与预测其碳储量动态变化提供重要科学依据。

(3) 发展碳汇扩增技术。随着全球海草床退化消失,海草床恢复^[67]及其凋落物的埋藏^[85]成为发展碳汇扩增技术的重要措施。因此,应深入开展海草床恢复技术应用推广,并筛选更多适合埋藏的植株凋落物。为增加海草床碳储量提供关键的技术支持。

(4) 开发海草床惰性有机碳的研究方法。由于提取惰性有机碳的常规方法繁琐,导致测量结果重复性差^[86,87]。因此,开发新的技术与方法,如加强热重量分析(thermogravimetric analysis, TGA)及交叉极化魔角自旋核磁共振分析(CP/MAS ¹³C NMR)等,为准确评估海草床蓝碳功能提供新的角度与途径。

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补充材料

表 S1 全球典型海草床沉积物有机碳及其可能来源的 $\delta^{13}\text{C}$

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Summary for “海草床沉积物储碳机制及其对富营养化的响应”

Mechanisms of sediment carbon sequestration in seagrass meadows and its responses to eutrophication

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Seagrass meadows are recognized as important and productive coastal ecosystems. They are globally-significant hotspots for sediment organic carbon (SOC) sequestration, storing about 4.2–8.4 Pg, and could up to 19.9 Pg SOC—an amount equivalent to 10-times that stored in the earth’s terrestrial soils. Sediment organic carbon (SOC) storage stocks in seagrass meadows are affected by SOC sources, composition and transformations. Unfortunately, seagrass meadows are declining globally at a rate of 5% per year mainly due to eutrophication, which could influence the supply (source), composition, and transformation of seagrass SOC. We systematically reviewed the literature of seagrass SOC sources, composition, transformation, and storage, as well as summarized their response to eutrophication. Seagrasses develop organic-rich sediment composed of both autochthonous and allochthonous organic carbon. Seagrass, epiphyte, macroalgae, and suspended particulate organic matter (SPOM) trapped from the water column can be common sources of sediment organic carbon in seagrass meadows. The main sources of SOC, however, are retained within seagrass and SPOM. According to a worldwide database of $\delta^{13}\text{C}$, the average contribution of seagrass to SOC is approximately 50%. The global average SOC content is 1.5%, with higher SOC concentrations have always been observed in the sediment of seagrass meadows compared to bare sediments. Additionally, there are significantly different of SOC contents between temperate regions and tropics. The SOC in seagrass meadows are composed of both labile organic carbon and recalcitrant organic carbon. Dissolved organic carbon and microbial biomass carbon are vital fractions of labile organic carbon, which are often served as an important indicator of change and future trends in SOC. Recalcitrant organic carbon is largely composed of belowground seagrass detritus. Sediment microorganisms determine the balance between SOC storage and remineralization processes within seagrass meadows, and high microbial activity and SOC transformation efficiencies are often observed in seagrass meadows. This is mainly due to excretion of amino acids, easily degradable sugars and oxygen, and suitable niches creation by the seagrass rhizosphere. However, the SOC transformation efficiencies decrease with increasing the sediment depth, which result in the high SOC sequestration potential. The main reasons for high SOC sequestration capacity of seagrasses are due to: high primary productivity, strong SPOM trapping capacity from the water column, and low decomposition rates. Although the sediment within seagrass meadows have high carbon sequestration capacity, carbon sequestration by seagrasses is spatially variable. The average SOC stock beneath seagrass meadows in the regions of East Asia, Southeast Asia and Australia are only quarter of the global average values. Eutrophication in coastal areas can trigger the overgrowth of algae, most commonly in the form of epiphytes and macroalgae within seagrass meadows. This cause algal material, which is more labile, to dominate SOC sources in seagrass meadows, consequently elevating microbial activities/biomass and accelerating SOC breakdown. Meanwhile, the nutrient-induced loss of seagrass biomass can decrease the capacity of organic carbon trapped from seawater. Therefore, changes of SOC sources, composition and transformation induced by nutrient loading can ultimately weaken SOC storage potential. As is often the case, there are exceptions in nature, and some studies have found no impact of nutrient loading on seagrass SOC content. Possibly there is a non-linear and hysteretic response of seagrass SOC to eutrophication, such that nutrient thresholds must be reached before responses can be detected. For future research, we recommend: (1) conducting studies of SOC storage stock at global scales; (2) strengthening the research of the effects of environment changes on storage mechanisms; (3) developing carbon sink amplification technologies; and (4) exploiting new methods for recalcitrant organic carbon measurements. The research of carbon sequestration in seagrass meadows should be strengthened in China, which could provide scientific perspectives for climate negotiations and CO₂ trading with other countries in the future.

seagrass meadows, sediment organic carbon, carbon storage, eutrophication, response

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