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评 述
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海草床退化与修复对其沉积物有机碳储存的影响过程

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摘要 海草床是近岸高生产力的生态系统之一, 具有巨大的碳储潜力, 是“蓝碳”的重要组成. 海草床生态系统中的有机碳大部分存储于沉积物, 其沉积物有机碳(sediment organic carbon, SOC)存储是“蓝碳”功能的重要体现. 受多重压力的影响, 全球海草床急剧衰退, 导致其SOC储存潜力下降. 近年来, 通过海草床修复来恢复其碳存储或扩增其碳汇能力逐渐受到重视, 对于延缓气候变化具有重要意义. 本文综述了海草床退化与修复对其SOC的影响过程. 研究表明, 海草床退化会导致海草源碳的贡献减少, 捕获颗粒有机物和阻止颗粒物再悬浮的能力下降, 进而直接降低海草床SOC储量; 此外, 海草床退化通过改变沉积物中的微环境, 加快SOC的转化, 间接减少已存储SOC的量. 海草床修复是提升碳储存潜力的有效手段, 可以增加海草植株碳对SOC的贡献, 其海草群落形成的复杂冠层结构可以减缓水流速度, 从而捕获更多细粒径的悬浮颗粒物. 同时, 海草床修复还可改变微生物群落, 从而抑制SOC的再矿化, 最终恢复甚至提高海草床的储碳功能. 在此基础之上, 本文提出未来的研究重点: (1) 研究人类活动和气候变化多因子联合作用对海草床SOC储存的影响过程; (2) 阐释海草床退化对SOC稳定性的影响机制; (3) 探索海草床SOC的组分和转化过程对修复的响应; (4) 构建基于SOC储量提升的海草床修复技术体系.

关键词 海草床退化, 海草床修复, 蓝碳, 沉积物有机碳, 碳汇

1 引言

海草床是近海具有极高初级生产力的海洋生态系统[1], 具有稳定底质[2]、为水生动物提供栖息地和食源[3]以及封存有机碳[4]等重要的生态功能. 近年来, 由于全球变暖逐渐加剧, 海草床的碳存储功能受到全球的广泛重视[5]. 尽管海草床占海洋面积的比例不足0.2%, 但每年对海洋有机碳埋藏贡献超过10%[6], 全球海草床生态系统的碳存储高达19.9 Pg, 其中超过90%存储于其沉积物中[7,8], 能够有效延缓全球气候变化[9].

然而, 受人类活动和气候变化的影响, 如富营养化、人为活动建设、挖掘、疏浚, 以及升温和海平面

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上升等多重压力都会导致海草床的快速退化[10,11]. 海草床的退化会导致其海草植株有机碳对碳存储贡献的下降, 降低其捕获水体颗粒物的能力, 从而直接降低其碳存储能力. 另外, 人类活动和气候变化等因素还会影响海草床已存储沉积物有机碳(sediment organic carbon, SOC)的转化过程, 导致海草床生态系统从吸收二氧化碳的“碳汇”转变为排放二氧化碳的“碳源”[12,13]. 因此, 亟待开展海草床修复工作, 以求恢复甚至增大其碳储存能力来延缓全球气候变化. 目前, 海草床修复的方法主要包括生境恢复法、种子播种法和植株移植法[14~16], 可以直接或间接提高海草生物量贡献、增加SOC的输入和促进沉积物厌氧环境来增加SOC的封存[17~19]. 据估算, 如果对海草床生态系统进行保护和修复, 到2030年将有830~2540万公顷潜在海草床面积被恢复, 恢复后的海草床最大缓解潜力可以达到209 Tg CO_2/a[5].

研究海草床退化和修复对其SOC储存的影响过程, 可以为认知全球碳汇对人类活动和气候变化的响应机制提供重要的科学依据. 本文主要从海草床退化和修复对SOC储存影响过程的研究进行总结, 旨在促进海草床的保护、管理和合理利用, 为执行有效的养护政策提供指导, 并为我国未来气候谈判、健全蓝碳标准体系和碳交易机制提供科技支撑.

2 海草床退化对其沉积物有机碳储存的影响过程与机制

海草床中大部分有机碳都存储于沉积物中, SOC的储存是其“蓝碳”功能的重要体现[7]. 海草床能够储存大量的SOC主要是因为海草本身具有较高初级生产力, 海草生物量以碎屑有机碳或溶解有机碳的形式储存于沉积物中[20]; 另一方面, 复杂的海草冠层可以捕捉水体悬浮颗粒物, 促进其沉降, 从而增加SOC的储存[21,22]; 此外, 沉积物提供的厌氧环境可以降低SOC的转化速率, 因此海草床有能力在沉积物中积累大量有机碳, 并在千年时间尺度上实现长期储存[12,23]. 如图1所示, 由于人类活动和气候变化的综合影响, 海草床逐渐破碎化和斑块化且恢复困难, 导致底质被侵蚀, 颗粒物再悬浮增加, SOC再矿化加剧, 海草床逐步丧失碳汇能力, 甚至转变为碳源[6,24](表1). 据统计, 从1990年开始, 海草床以每年7%的速率衰退[39], 造成的碳损失约为299 Tg C/a[7], 经济损失高达1.9×10^9~13.7×10^9 \$/a[25].

2.1 海草床退化减少海草和颗粒物对沉积物有机碳的贡献

人类活动和气候变化引起的海草床退化可直接导致海草生物量碳下降[24,40]. 海草生物量碳是海草床SOC的重要组成部分, 储存在沉积物中的有机碳主要

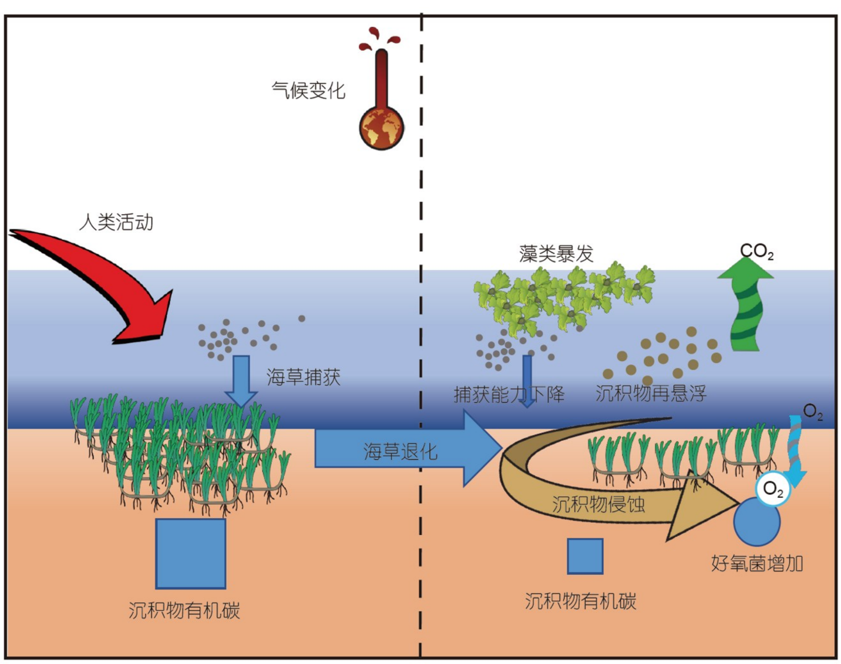

图 1 海草床退化碳损失示意图
Figure 1 Schematic diagram of loss of organic carbon in degraded sediments of seagrass meadows

表 1 退化海草床沉积物的碳损失及其原因[a)]

Table 1 Carbon loss in degraded seagrass meadows sediments and its causes

地区	海草种类	碳损失	损失原因	文献
全球	–	0.01~0.09 Pg C/a	人类活动和气候变化	[25]
瑞典斯卡格拉克海岸(Gullmar Fjord)	鳗草(*Zostera marina*)	5.5% ± 1.7% C	沉积物再悬浮	[26]
瑞典北海岸	鳗草	60.2 Mg C/ha	沉积物流失	[27]
加勒比(Little Cayman, Cayman Islands)	龟裂泰来草(*Thalassia testudinum*)	51% C	沉积物再悬浮	[28]
肯尼亚(Gazi Bay)	波喜荡草属	2.21 Mg C/ha	海草移除	[29]
西班牙加利西亚(Toralla Island)	鳗草	2 kg C/m^2	过度捕捞	[30]
葡萄牙(Ria Formosa)	诺氏鳗草(*Zostera noltii*)	28.9 Mg C/ha	基础设施建设	[31]
塞浦路斯	大洋波喜荡草(*Posidonia oceanica*)	15% C	渔业养殖	[32]
美国弗吉尼亚州(South Bay)	鳗草	321 g C/m^2	海洋热浪	[33]
澳大利亚	–	3.3~4.6 Gg C/a	海草损失	[8]
澳大利亚西海岸(Cockburn Sound)	波喜荡草属	0.02~0.04 Tg C 3~5.7 Tg C	富营养化	[34]
澳大利亚东南部(Sunday Island)	澳洲波喜荡草(*Posidonia australis*) 黑茎鳗草(*Zostera nigricaulis*)	3.9~5.4 t C/ha	过度放牧	[35]
澳大利亚东海岸(Jervis Bay)	澳洲波喜荡草	~0.6 kg C/m^2	需氧异养菌增加	[19]
澳大利亚西海岸(Shark Bay)	澳洲波喜荡草 南极根枝草 (*Amphibolis antarctica*)	0.55~2.45 Tg C	海洋热浪	[36]
		1500 g C/m^2	水质恶化	[37]
澳大利亚西部(Oyster Harbour)	澳洲波喜荡草	280~310 Mg C	富营养化	[38]
		9.27~11.18 Gg C	再矿化	[38]

a) “–”表示文献中未提及相关信息; “C”表示沉积物有机碳

来自凋落物生物量和活体生物量[20]. 全球海草生物量储存的有机碳平均为2.52±0.48 Mg C/ha, 其中2/3输送到地下茎和根部[7], 累积速率为41~66 g C/(m^2 a)[2,21]. 海草植株密度和生物量紧密相关, 海草床退化过程中海草植株密度的变化可以作为量化生物量变化的指标[41]. 随着富营养化程度加剧, 新泽西州鳗草(*Zostera marina*)的植株密度从292株/m^{2}下降到241株/m^2, 叶片长度从31.83~34.02 cm下降到18.60~19.37 cm, 地上生物量和地下生物量分别下降了50.0%和87.7%[42]. 此外, 海洋热浪导致美国弗吉尼亚州南湾(South Bay)鳗草植株密度从599株/m^{2}下降到43株/m^2, 减少了93%, 使上层SOC(0~5 cm)从571±27 g C/m^{2}下降到250±21 g C/m^2[33]. 海草作为SOC的主要来源[43,44], 对SOC的平均贡献可以达到50%[21,45], 有些海域甚至高达80%[36,46]. 但是, 海草床退化会导致海草对SOC贡献显著降低. 例如, 巴利阿里群岛(Balearic Island)大洋波喜荡草(*Posidonia oceanica*)在保护较好的原生草床中对SOC的平均贡献率高达80%±9%, 但在受中、高人为压力的情况下, 平均贡献率则仅为52%±12%, 海草对SOC的贡献下降了将近30%[46].

海草对颗粒有机物的捕获主要通过海草冠层捕获和附着生物的主动摄入[47], 增强沉积作用的同时减少沉积物的再悬浮作用[2], 从而增加SOC储量. 例如, Ricart等人[47]在评估海草床SOC储量的景观异质性时, 发现海草床的悬浮颗粒物沉积速率较裸地沉积速率高出3~5倍. 此外, 西班牙东北部巴塞罗那的大洋波喜荡草海草床沉积物中可以封存198 g C/(m^2 a), 其中72%来自海水的悬浮颗粒物[48], 与裸地沉积物相比, 海草可以有效阻止沉积物再悬浮, 沉积物再悬浮量减少了3倍以上[2]. 但是, 近年来, 海草床破碎化日益严重, 导致海草捕获颗粒有机物和阻止颗粒有机物悬浮的能力下降, 进而降低了SOC储量[49,50]. Salinas等人[34]认为, 20 cm/s是SOC侵蚀的水流流速关键阈值. Dahl等人[26]发现, 海草床沉积物再悬浮浓度与水流速度呈显著正相关, 当水流速度为5 cm/s时, 平均再悬浮浓度为0.13±0.02 mg/L; 水流速度增加到26 cm/s时, 平均再悬浮浓度达到1.26±0.2 mg/L. 沉积物的再悬浮会降低海草床SOC储量. 例如, 加勒比海域由于动物摄食造成龟裂泰来草

(*Thalassia testudinum*)叶冠急剧较少，导致大量沉积物再悬浮，占到总沉积物通量的51%[28]．渔民大量捕获蛤蜊(*Dosinia exoleta*)，导致西班牙的海草床鳗草植株密度和生物量分别下降了63%和64%, 造成海草床沉积物大量流失，最终SOC减少了50%，平均损失达到2 kg C/m^2[30]．

2.2 海草床退化促进沉积物有机碳的转化

沉积物可以为有机碳提供持续稳定的厌氧环境，且97%的SOC以难降解的木质素和黑碳等形式存在, 这是海草床SOC分解缓慢以及可以千年时间尺度长久封存于沉积物的重要原因[12,51]．在人类活动和气候变化的影响下，沉积物厌氧环境、微生物群落和胞外酶活性发生变化, 影响了海草床SOC的分解, 从而改变海草床SOC储量. 例如, 人类活动(如船只锚定、系泊活动和螺旋桨划痕)导致海草破碎化和斑块化且恢复困难，造成沉积物侵蚀[52]，大规模的扰动引发土壤-水界面的垂直混合, 从而促进氧气进入沉积物表层和扩散[53], 导致好氧异养生物如脱硫杆菌科相对丰度升高，并提高微生物活性, 加剧深层沉积物的有机碳再矿化, 有机碳周转率增加了34~38倍，最终会导致海草床沉积物中封存的SOC以CO_2形式重新释放[12,13,54]．在2010~2011年热浪事件之后，澳大利亚西海岸海草床开始大面积退化，SOC暴露在氧气中导致再矿化速率加快，假设10%~50%海草床SOC暴露在氧化条件下，3年后将导致2~9 Tg CO_2被释放到空气中[36]．Pedersen等人[23]在室内厌氧条件下模拟升温对大洋波喜荡草SOC影响的实验中发现, 当温度从15°C升高到25°C时, SOC矿化速率提高了4.5倍．这表明全球升温会导致海草床微生物活性增强, 造成SOC损失. 此外, 澳大利亚东海岸的研究表明，受到干扰后的澳洲波喜荡草(*Posidonia australis*)沉积物中好氧异养细菌假交替单胞菌(Pseudoalteromonas)的比例显著升高，导致SOC储量损失达到72%[19]，而澳大利亚西部由于富营养化引起的海草床SOC再矿化导致最终有34~41 Gg CO_2被释放[38]．

人类活动引起海草床退化还会改变其SOC的来源和组成, 进而影响其SOC的转化过程. 以富营养化为例, 富营养化通常会增加藻类对SOC的贡献．1970年以来, 奎布雷湾海草床沉积物颗粒碳稳定同位素更接近微藻, 表明藻类作为碎屑中碳源的重要性日益增加[55]．在海南新村湾海草床中, 相较于远离养殖区, 靠近养殖区的海草床中藻类对SOC的贡献增加了16%[44]．藻类比海草含有更多的活性有机碳[56]，因此藻类贡献的增加会导致海草床沉积物中活性有机碳的增加. 例如, 靠近养殖区的海草床存在大量大型藻类碎屑，大型藻类的快速分解导致沉积物中活性有机碳含量增加[57]，沉积物活性有机碳库含量达到260 mg/kg，而低营养区仅为200 mg/kg[58]．沉积物活性有机碳是SOC最活跃的那部分碳库，主要包括碳水化合物、氨基酸和蛋白质等物质[59]，是环境变化的重要指示[60]．人类活动会导致活性碳的输入，促进沉积物中微生物对惰性有机碳的转化过程．Liu等人[61]在海南新村湾的研究发现，富营养化会导致真菌群落向腐生真菌转变，如Trapeliales、球囊霉(Glomerales)、多孢囊霉目(Diversisporales)、肉座菌目(Hypocreales)和粪壳菌目(Sordariales), 这些真菌具有重要的纤维素酶和木质素过氧化物酶的功能，可以促进沉积物中惰性有机碳如纤维素和木质素的分解, 从而降低SOC的长期储存．富营养化诱使附生藻类、大型藻类和海草叶片凋落物输入量的增加，使得分解有机碳的胞外酶活性(多酚氧化酶、α-葡萄糖苷酶、β-葡萄糖苷酶、木质素过氧化物酶、转化酶和维生素酶)提高1.2~4.66倍[43,61]，微生物生物量碳含量增加，巨型藻类(*Cladophora* spp.)的分解会提高活性有机碳含量，最终导致海草床SOC矿化并释放大量CO_2[57]．Trevathan-Tackett等人[13]的室内实验结果表明，新鲜碳的添加能够诱发微生物激发反应，刺激沉积物释放1.7~2.7倍的CO_2．因此，海草沉积物中有机碳的来源、组成和转化显著影响了其SOC储存能力．但SOC中除活性有机碳外, 还含有丰富的惰性有机碳. 惰性有机碳是SOC库中最为稳定的有机碳库，其主要成分为木质素和其他酚类物质，能够有效抵抗微生物的分解，是SOC库中最重要的长期储存组分[12,62]. 目前，仅开展了海草床沉积物惰性碳含量的初步研究. 例如, 海南地区泰来草(*Thalassia hemprichii*)和海菖蒲(*Enhalus acoroides*)的惰性有机碳储量分别达到303.3~496.6和330.2~690.1 mg/kg，占到SOC碳库的24%~44%[61]. 可见，目前多关注海草床SOC和其活性有机碳的来源、组成及转化，沉积物中的惰性有机碳是SOC最重要的存储组分，关于沉积物惰性有机碳在海草退化过程中的变化及其影响因素, 尚缺乏认识.

3 海草床修复对沉积物有机碳储存的影响过程与机制

目前，海草床修复方法主要有生境恢复法、种子

播种法和植株移植法[14~16,63]，通过对海草床进行移植修复，逐渐恢复其碳汇能力. 如图2和表2所示，海草床修复过程中，海草初级生产力逐渐恢复，海草植株密度逐步增加，进而减少沉积物的侵蚀、再悬浮和氧化，使得海水中悬浮颗粒物得以重新捕获并沉积下来，并且较细粒径沉积物比例逐渐增加，沉积物内氧气输入减少，最终SOC储量恢复到天然成熟海草床的水平[33,64]. 但是，目前修复实验的研究主要关注海草的存活率、覆盖率及SOC总量的变化[64]，而修复过程中SOC组分(活性有机碳和惰性有机碳)变化和转化过程鲜有报道，亟待开展相关研究.

3.1 海草床修复增加海草和颗粒物向沉积物的有机碳输入

海草植株密度是海草床初级生产力的驱动者[64]，海草床修复可以通过增加海草植株密度来促进初级生产和增加生物量，进而提高植株对SOC储量的贡献. 在海草移植修复过程中，植株密度是变化最显著的指标，海草植株密度和海草地上生物量紧密相关，同时也是海草初级生产力的主要驱动因素[41,64]，干扰后的快速植株恢复是最大程度地减少海草蓝碳净损失的关键[33]. 海草床SOC在不同海草植株密度下会呈现出显著的差异，密度大的自然连续分布的大洋波喜荡草、小丝粉草(*Cymodocea nodosa*)[71]、鳗草[72]、牟氏鳗草(*Zostera muelleri*)[47]、龟裂泰来草和莱氏二药草(*Halodule wrightii*)[73]等海草床沉积物，会比稀疏的斑块分布的海草床沉积物和裸地多埋藏20%的SOC[74]. Samper-Villarreal等人[75]认为，海草结构复杂性越高，即叶面积指数、地上生物量和地下生物量越高，海草对SOC的贡献越高. 美国猪岛湾(Hog Island Bay)海草床邻近的裸地中鳗草对SOC贡献率仅为29%, 修复4年后，海草的贡献率达到50%, 修复的第10年海草床沉积物至少可以比裸地多储存14.3 g C/m^2[76]. 此外，通过播撒种子恢复美国弗吉尼亚南湾鳗草海草床，使鳗草的地上初级生产力提升了20倍，海草床5 cm深沉积物的碳储量是裸地沉积物的2倍，分别为278.9和138.7 g C/m^2，其中50%有机碳是由海草贡献[64]. 在格陵兰岛Kapisillit地区，鳗草生物量最大时对SOC的贡献也最大，使得Kapisillit地区SOC达到595 g C/m^2, 远高于海草贡献最小的Kobbefjord地区SOC碳储量(446 g C/m^2)[77,78]. 国内也已开展海草床修复研究，但多集中于探讨海草移植技术和效果评估的探索. 例如，张沛东等人[79,80]探索了海草种子移植技术，创新性地采用粗麻布袋种植种子的方法对鳗草进行修复，有效提高了鳗草种子的建成率. 刘松林等人[81,82]研究发现，不埋藏、较高水温和细粒径沉积物条件可促进热带海草海菖蒲种子和幼苗生长，为野外热带海草种子和幼苗移植提供科技支撑. 李森等人[63]认为，植株移植法是国内海草修复的首选方法. 陈石泉

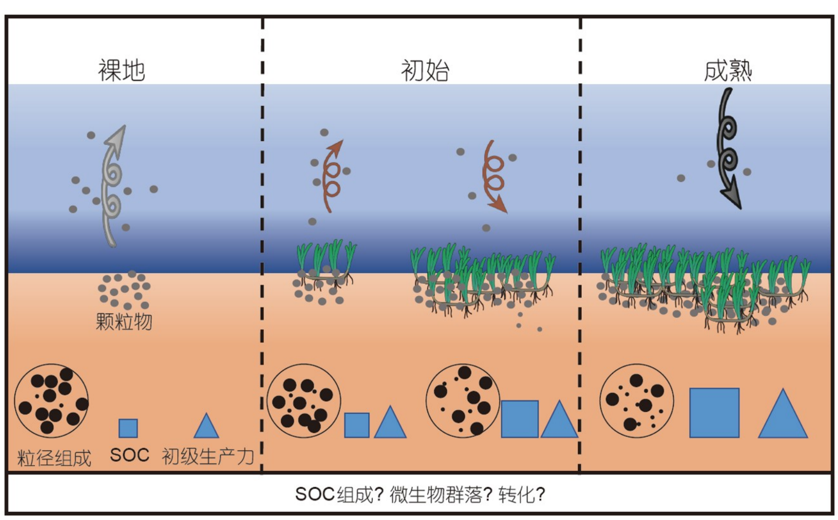

图 2 海草床修复过程中沉积物组成、粒径组成和有机碳的变化示意图. 箭头代表颗粒物再悬浮或沉积; 方块大小代表SOC储量; 三角形代表初级生产力; 圆圈内不同尺寸大小的圆比例代表修复过程中粒径组成的变化. 修改自文献[61]

Figure 2 Schematic diagram of changes about sediment composition, sediment particle size proportions and sediment organic carbon during seagrass meadows restoration. Arrows represent particle resuspension or deposition; block size is SOC storage; triangle is rates of primary productivity; the ratio of circles with different sizes within the big circle is equivalent to the change in particle size composition during recovery process. Modified from Ref. [61]

表 2 海草床修复过程中沉积物碳埋藏速率和碳储存变化[a)]

Table 2 Changes of sediment carbon burial rate and carbon storage during seagrass meadows restoration

地区	海草种类	修复前	修复后	文献
美国(South Bay, Virginia)	鳗草(*Zostera marina*)	250 g C/m^2	317 g C/m^2	[33]
		249 g C/m^2	372 g C/m^2	[33]
		138.7 g C/m^2	278.9 g C/m^2	[64]
		–	36.68 g C/(m^2 a)	[65]
		2489 t C	3662 t C	[66]
		630 t C/a	15000 t C	[67]
		1130 t C	2010 t C	[68]
		196 g C/m^2	292 g C/m^2	[68]
		346 t CO_2/a	1070 t CO_2/a	[68]
澳大利亚西部(Oyster Harbour)	澳洲波喜荡草(*Posidonia australis*)	16.2 g C/m^2	26.4 g C/m^2	[37]
澳大利亚西海岸(Cockburn Sound)	波状波喜荡草(*Posidonia sinuosa*)	0.6 kg C/m^2	6.0 kg C/m^2	[69]
	波状波喜荡草	1.2 g C/(m^2 a)	12.1 g C/(m^2 a)	[69]
	小丝粉草(*Cymodocea nodosa*)	2.4 t C/ha	90.27 t C/ha	[70]
	莱氏二药草(*Halodule wrightii*)	14.73 t C/ha	364.64 t C/ha	[70]
	丝状针叶草(*Syringodium filiforme*)	8.89 t C/ha	175.36 t C/ha	[70]
	鳗草	0.71 t C/ha	48.27 t C/ha	[70]
	诺氏鳗草(*Zostera noltii*)	3.52 t C/ha	106.91 t C/ha	[70]

a) “–”表示文献中未提及相关信息; “C”表示沉积物有机碳

等人[83]提出了采用海草盖度、新分枝率、新生长芽以及海草株数等指标来评估热带海草移植的效果. 邱广龙等人[84]通过移植探索发现, 日本鳗草(*Zostera japonica*)、卵叶喜盐草(*Halophila ovalis*)和贝克喜盐草(*Halophila beccarii*)适宜在广西潮间带进行移植. 然而, 国内亟待开展海草移植修复对SOC储存能力影响的研究. 已有研究主要集中于北半球温带鳗草的移植修复及其修复过程中SOC存储量的变化[85], 但是关于亚热带和热带海域尤其是西太平洋海草移植对SOC储量影响的研究, 仍鲜见报道.

海草床修复过程中海草冠层可以通过减缓水流捕获较细粒径的颗粒物来增加SOC储量(图2). Barcelona等人[86]研究发现, 恢复后的鳗草将水底流速降低了70%~90%, 波浪高度降低了45%~70%, 当海草冠层覆盖率超过52.1%时, 海草冠层能够捕获更多的细颗粒物. 丹麦霍森斯峡湾(Horsens Fjord)大规模鳗草移植成功2年后, 沉积物粒度降低, 证实移植的鳗草冠层对细颗粒的保留是沉积物中碳埋藏的主要驱动因素, 有机碳和无机碳沉降速率可以达到33±7.5和290±22 g/(m^2 a)[87]. 此外, 澳大利亚澳洲波喜荡草修复实验表明, 随着海草床的逐渐修复, 海草床捕获外源碳的能力增加, 其中悬浮颗粒物占到SOC的27%, 远高于裸地的12%, 海草床修复实验进行18年后, 海草床SOC达到252±38 g C/m^2[37]. 另一方面, 海草床修复还可以通过增高并复杂化海草冠层来促进颗粒有机物沉积并阻止沉积物再悬浮, 从而增强沉积物中的碳埋藏[2]. Orth等人[88]在中西部大西洋沿海潟湖鳗草修复实验中发现, 随着海草床面积的扩大, SOC储量呈指数级增长, 沉积物碳净储量可以达到3000 T.

3.2 海草床修复抑制沉积物有机碳的转化

海草床沉积物中微生物的活动在SOC转化过程中起到关键作用[12,54], 并在海草和裸地形成不同的微生物群落. 例如, 海南新村湾和潭门港海草床(海菖蒲和泰来草)的根际微生物主要以变形杆菌(Proteobacteria)为主, 其中新村湾海草根际变形菌属主要组群为(Desulfobacteraceae)、螺杆菌科(Helicobacteraceae)和脱硫球菌科(Desulfobulbaceae), 而相邻的裸地则主要以厚壁菌门(Firmicutes)为主. 潭门港海草根际变形菌主要包括弧菌科(Vibrionaceae)和脱硫杆菌科, 但是裸地的优势族群为Woeseiaceae[89]. 这一点与Brodersen等人[90]的研究结果类似, 即海草根际具有丰度更高的硫酸盐氧

化细菌. 在地中海大洋波喜荡草中, 海草床沉积物细菌的$\delta^{13}C$与海草相似, 海草床中硫化还原速率和总还原硫量也都高于裸地, 说明细菌优先分解海草有机物, 与海草邻近裸地沉积物中的细菌则优先消耗SOC[91]. 在修复后的海草床0~10 cm深沉积物中, 微生物量碳占总SOC的24%~38%, 而遭到破坏的海草床沉积物中微生物量碳仅占到SOC的17%~20%[92,93]. 这表明在修复过程中海草床沉积物微生物群落组成发生了显著的变化. 微生物群落组成的显著差异表明, 海草具有强烈的"根际效应", 能够有效阻止海草床SOC的再矿化. 在澳大利亚的研究发现, 从受破坏的裸地到逐步恢复的海草床, 厌氧微生物δ-变形杆菌(δ-proteobacteria)和梭菌属(Clostridium)的丰度显著增加, 而好氧的假交替单胞菌属(Pseudoalteromonas)丰度则逐渐减少, 使得SOC含量明显增加, 达到裸地的2倍多[19,94]. 此外, 海草床的修复可以改变沉积物的氧化还原电位和溶氧等微环境来影响微生物群落组成, 进而影响SOC的再矿化. 例如, 泰国西南沿海的研究表明, 海草床沉积物中的氧化还原电位((-146.7 ± 18.1)~(-97.1 ± 12.1) mV)往往低于邻近裸地沉积物的氧化还原电位(-22.9 ± 55.1 mV)[95], 且海草沉积物中具有更多有机物. 这表明海草有助于降低其根际周围沉积物的氧化还原电位, 进而减弱硫酸盐还原菌的反应, 有利于海草床沉积物封存更多的有机物[96]. 因此, 探讨海草床修复过程中沉积物有机碳组分及其转化的动态变化, 对揭示海草床移植过程中SOC的提升机制具有重要意义. 然而, 目前全球海草床修复主要集中于其修复效果和SOC总量提升的描述, 但是其SOC组分和转化对修复的响应过程却鲜见报道, 亟须开展相关研究.

4 研究展望

综上所述, 尽管海草床退化和修复对SOC储存的影响已经进行了研究, 但是仍有不足之处, 未来仍需进行以下几方面的研究.

(1) 探究人类活动和气候变化多因子联合作用对海草床SOC储存的影响过程. 人类活动扰动、全球变暖、海平面上升、海水酸化等会导致海草资源量明显退化, 直接或间接降低海草床的固碳能力[97,98]. 但目前关于单一扰动因素对海草床沉积物储碳影响的研究较多, 而多因子对储碳的综合影响并未有报道. 在人类活动和未来全球气候变化的条件下, 海草床受到多种因子的复合影响, 未来需要开展多因子对海草床沉积物储碳综合影响的研究, 深入揭示海草床沉积物碳储对复杂变化的响应过程.

(2) 阐释海草床退化对SOC稳定性的影响机制. 惰性有机碳是能够在海草床沉积物中长期保存下来的那部分SOC, 代表了SOC库的稳定性[99]. 然而, 目前多关注海草床退化对总SOC和其活性有机碳含量的影响, 关于海草床沉积物中惰性有机碳的研究有限, 对其含量、组分及其影响因素仍缺乏认知. 因此, 未来需要深入开展海草床退化对沉积物惰性有机碳的研究, 为评估全球海草床碳储的稳定性提供重要的科学支撑.

(3) 探索海草床SOC的组分和转化过程对修复的响应研究. 海草床SOC的组分是决定其是否能长期存储的基础, 微生物在SOC转化过程中起到关键作用, 能够直接或间接通过分泌胞外酶等酶来分解SOC[100]. 但目前海草床修复实验主要聚焦于海草床沉积物总SOC量的变化, 未来需深入探索海草床修复对SOC组分和转化的影响, 以阐明海草床修复对海草床SOC储量提升的驱动机制.

(4) 构建基于SOC储量提升的海草床修复技术体系. 在全球碳中和的战略目标下, 亟待开展海草床修复以提升其碳储潜力. 尽管国内开展了丰富的海草移植实验, 但多关注于海草移植效果的评估和移植技术的探索. 目前, 海草床修复对SOC储量提升的研究主要集中在大西洋、地中海、澳大利亚等温带海域[85], 关于亚热带和热带海草床修复对SOC储量提升潜力的影响, 仍未见报道. 因此, 根据亚热带和热带海草床生境特点, 构建基于SOC储量提升的海草床修复技术体系, 对促进海草床碳储功能的恢复和缓解全球气候变化具有重要意义.

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Summary for "海草床退化与修复对其沉积物有机碳储存的影响过程"

Influence processes of seagrass degradation and restoration on sediment organic carbon storage

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Seagrass meadows are important coastal ecosystems with high levels of productivity. They generally have significant carbon storage potential and are important components of "blue carbon". Seagrass ecosystems can store up to 19.9 Pg organic carbon, more than 90% of which is stored in sediments. Protecting the organic carbon stored in seagrass meadows sediments is therefore considered an important means of mitigating climate change. Unfortunately, approximately 29% of seagrass meadows have disappeared due to the influence of human activities and global climate change. They have been declining at a rate of 7% per year since 1990, resulting in the release of up to 299 Tg of carbon per year. The restoration of seagrass meadows has become one of the most important means for mitigating the continuing loss of seagrass habitat and preventing them from being a significant carbon source. A systematic review of relevant national and international research was conducted to summarize the response processes and mechanisms of sediment organic carbon (SOC) during seagrass meadow degradation and restoration. Seagrass biomass carbon is an important source of SOC. However, eutrophication and ocean warming have important negative impacts on seagrass biomass carbon, thereby reducing its contribution to SOC. Suspended particulate matter contributes approximately 70% to SOC, but the increasing patchiness and fragmentation of seagrass meadows significantly reduces its capture by the seagrass canopy. This significantly decreases the sedimentation of suspended particulate matter. Furthermore, the degradation of seagrass meadows could lead to the exposure of bare sediments and deep sediments to human activities and wind waves, which would alter the microbial environment of sediments and induce the remineralization of SOC. All of these directly or indirectly reduce the carbon storage and carbon sequestration capacity of seagrass meadows. Recently, the response of SOC to a single disturbance factor has been estimated, but the uncertainties of multiple factors remain. In the future, the comprehensive interference of human activities and global climate change will drive SOC trends. Approximately 68% of the global seagrass restoration experiments have been concentrated on the temperate and subtropical coasts of the Northern Hemisphere. The main restoration methods are habitat restoration, seeding, and plant transplantation, all of which can effectively increase the carbon storage potential of seagrass meadow sediments. Seagrass shoot density is the key driver of seagrass primary productivity and the most significant indicator of changes in the restoration process. It is closely related to the aboveground biomass of seagrass. Rapid plant recovery after disturbance is the key to minimizing blue carbon net loss in seagrass meadows. Increasing the density of seagrass shoots would increase the complexity of the seagrass canopy. On the one hand, this is beneficial for trapping suspended particulate matter. On the other hand, it can effectively reduce the flow of seawater, thus promoting the sedimentation of suspended solids and increasing their contribution to SOC. The microbial environment of the sediment changes during the restoration process, which can weaken the remineralization of organic carbon and enable the storage of SOC for a long time. As the most widespread area seagrass area in China, the seagrass meadows in South China are severely degraded and SOC has not yet been systematically studied. Several key points of research on the response mechanisms of seagrass meadow SOC to degradation and restoration were proposed. (1) To determine the comprehensive contributions of human activities and climate change to SOC storage in seagrass meadows. (2) To elucidate the mechanism of seagrass meadow degradation influence on SOC stability. (3) To investigate the effects of seagrass restoration on the composition (labile organic carbon and recalcitrant organic carbon) and transformation process of SOC. (4) To develop a technical system for seagrass restoration based on the enhancement of SOC storage. Such studies based on local seagrass ecosystems will contribute to improving research on the global seagrass carbon storage system.

seagrass degradation, seagrass restoration, blue carbon, sediment organic carbon, carbon sinks

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