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# 硅的生物地球化学过程及其在养殖碳汇形成过程中的作用和影响\*

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**摘要** 硅(Si)是地球上丰度仅次于氧的第二大元素, 其生物地球化学过程与大气 CO<sub>2</sub> 变化、海洋生物泵以及海岸带富营养化等过程密切相关, 因此, 硅循环也成为全球环境变化研究关注的核心问题之一。本文在总结已有研究的基础上, 论述了硅生物地球化学过程及其对碳循环的调节及影响, 进一步聚焦近海规模化贝类养殖活动, 分析了贝类养殖生态系统硅循环与碳循环的耦合作用及机理, 展望了未来值得关注的科学问题。研究表明, 地质尺度上, 硅酸盐矿物风化是地表所有次生硅的来源, 风化过程也是一个重要的碳汇过程。陆地生态系统中, 植硅体较难降解, 在其形成过程中会包裹有机碳而形成稳定的有机碳库, 因而植硅体碳具有重大的碳汇潜力, 很有可能成为全球碳汇的重要组成部分。海洋生态系统中, 作为初级生产主要贡献者的硅藻(Bacillariophyta)吸收硅酸盐合成有机碳并将其打包在生源硅颗粒中向深层海洋输送并埋藏, 埋藏量可占海洋碳埋藏总量的40%, 生物硅泵驱动了生物碳泵; 在近海贝类养殖区, 通过硅藻作为滤食性贝类的饵料来源, 硅酸盐成为渔业碳汇重要的物质支撑。因此, 研究硅生物地球化学循环过程中, 综合考虑各过程及其耦合作用是非常必要的, 对深入了解其在贝类养殖碳汇中的作用及探究潜在养殖增汇途径具有重要意义。

**关键词** 硅循环; 硅藻; 植硅体; 生物硅; 碳汇; 贝类养殖

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工业革命以来, 大气中 CO<sub>2</sub> 浓度不断升高, 引起一系列环境问题(IPCC, 2022)。为应对气候变化新形势, 我国响应自主减排并提出“争取 2060 年实现碳中和”的宏伟目标, 因此, 加快推动低碳循环发展, 努力探求碳增汇途径成为当前形势下的重要举措

(张永雨等, 2017)。占地球表面积 70%的海洋是地球上最大的活跃碳库, 尤其是深海被认为是大气中 CO<sub>2</sub> 的最终和合理归宿, 海洋每年净吸收的 CO<sub>2</sub> 约有 80.7 Gt (1 Gt = 10<sup>9</sup> t) (Sabine *et al.*, 2004), 1960—2018 年表层海洋吸收了 21%~27% 的人为排放 CO<sub>2</sub> (Friedlingstein *et al.*,

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2019)。但这部分碳并不稳定,经呼吸、降解等过程会再次释放到大气中。因而,寻找长期稳定的碳汇机制受到越来越多的关注(Song *et al*, 2016; Jiao *et al*, 2018、2020; Zhang *et al*, 2020)。

硅(Si)是地球上仅次于氧的第二大元素,约占地壳质量的 28.8% (Wedepohl, 1995),作为海洋主要初级生产者——硅藻(Bacillariophyta)的主要构成元素,是海洋中重要的营养元素,其生物地球化学行为在调节陆地和海洋初级生产力、全球气候变化中发挥着关键作用(Sutton *et al*, 2018)。根据其赋存形态不同,自然界中的硅可简单划分为两大储库:陆壳和洋壳岩石中的原生硅酸盐矿物储库及原生硅酸盐矿物风化后形成的次生硅酸盐矿物[包括溶解态硅(dissolved silicate, DSi)和无定形硅(amorphous silica, ASi)],在不同的陆地和海洋环境中经地球化学或生物化学沉积形成储库(Basile-Doelsch, 2006)。硅在不同储库间经

过一系列生物地球化学过程进行迁移和转化(图 1)(Struyf *et al*, 2009)。首先,陆地硅酸盐矿物风化过程释放出可溶性的硅酸盐,部分硅酸盐很容易被陆地植物吸收形成植硅体(Conley, 2002),另有部分经河流输送至海洋,在输送过程中,通过生物泵生成生物硅(biogenic silica, BSi),最终以颗粒态沉降并埋藏至沉积物中。这一系列过程,均与碳在大气、陆地和海洋三大储库间的迁移和储存相关联。全球尺度上,硅元素经由陆地风化和海洋沉积与碳循环紧密相连(Ragueneau *et al*, 2000)。了解硅循环对于了解海洋食物网、生物地球化学循环和生物碳泵的功能至关重要(Tréguer *et al*, 2021)。因此,本文在前人研究基础上,总结硅的生物地球化学过程及其与碳循环相关的关键过程研究,综述硅元素在碳循环中发挥的作用和调控机制,并对养殖水域中硅生物地球化学过程的变化及其在渔业碳汇领域起到的作用进行探讨与展望。

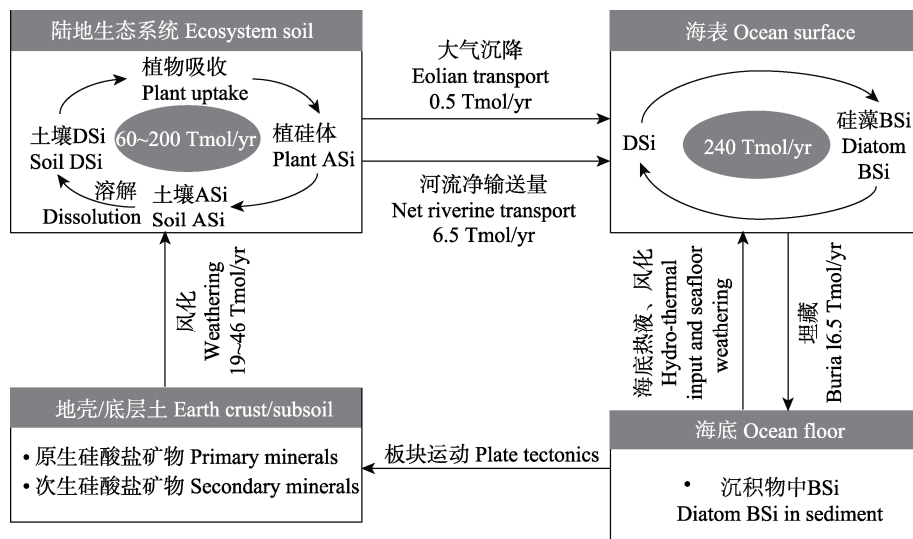


图 1 全球硅的生物地球化学循环(Struyf *et al*, 2009)

Fig.1 The global biogeochemical cycle of silicon (Struyf *et al*, 2009)

DSi、ASi 和 BSi 分别指溶解态硅、无定形硅和生物硅。

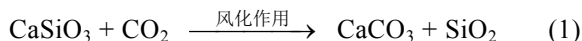
DSi, ASi, and BSi represent dissolved silicate, amorphous silica, and biogenic silica, respectively.

## 1 硅的生物地球化学循环及其在碳循环中的作用

### 1.1 硅酸盐矿物风化

作为宇宙中第七丰富的元素(Tréguer *et al*, 2013),硅在地壳中主要以硅酸盐矿物的形式存在于火成岩、变质岩和沉积岩中(Ittekkot *et al*, 2006; Sommer *et al*, 2006)。硅氧化物在所有矿物中的比例可达 90% (Struyf *et al*, 2009),但其中仅很小一部分硅

会参与到生物地球化学循环过程中(Conley, 2002)。岩石中的硅酸盐矿物通过风化作用,转变为粘土和泥沙、原硅酸( $H_4SiO_4$ )和生物硅等。硅酸盐矿物的风化过程需要  $CO_2$  的参与(Street-Perrott *et al*, 2008):



式中,  $CaSiO_3$  代表硅酸盐矿物。在这一反应中,碳最终以碳酸盐矿物的形式被埋藏。硅酸盐矿物的化学风化及其产物的循环构成了全球硅生物地球化学及硅与其他元素(如碳、氮)循环相互作用的基础(Ittekkot

*et al*, 2006; Subramanian *et al*, 2006)。这一反应过程中所消耗的  $\text{CO}_2$  来自于大气或土壤中植物降解所产生的  $\text{CO}_2$  (Subramanian *et al*, 2006)。因此, 地质尺度上(数千至百万年)认为, 陆地硅酸盐的风化作用是大气  $\text{CO}_2$  的重要碳汇(Gaillardet *et al*, 1999; Liu *et al*, 2000), 这一过程在调节大气及海洋中  $\text{CO}_2$  浓度和全球气候变化中发挥着重要作用(Berner, 1995; Kump *et al*, 2000)。据估测, 每年大约有 0.26 Gt 的碳通过全球岩石风化过程从大气-生物圈转移到海洋中(Hartmann *et al*, 2010)。我国境内河流域硅酸盐矿物通过风化每年可消耗大气中 5.05~7.52 Mt (1 Mt =  $10^6$  t) 的  $\text{CO}_2$ , 占全球河流消耗总量的 4.8%~7.1% (吴卫华等, 2011)。地质时间尺度上, 硅酸盐矿物风化也被认为通过一种负反馈机制来维持地球气候的宜居性, 因此, 也被称为气候“恒温器”(Misra *et al*, 2012; Caves Rugenstein *et al*, 2019)。经典的负反馈假说认为, 火山排气引起的  $\text{CO}_2$  释放量增加最终会导致地表升温, 温度升高则会促进硅酸盐矿物风化进而大量消耗  $\text{CO}_2$ , 最终将大气中的  $\text{CO}_2$  维持在一个稳定水平(Berner *et al*, 1997; Deng *et al*, 2022)。硅酸盐矿物风化和  $\text{CO}_2$  间的这一关系也曾被 Andrews 等(2001)在室内实验中的短时间尺度上观测到, 当提高大气  $\text{CO}_2$  浓度时, 硅酸盐矿物的风化会增强。

硅酸盐矿物风化产生的溶解产物通过河流输送至海洋的过程中, 会被生物吸收。溶解态硅是许多高等植物和硅藻生长必须的营养元素, 在生物同化作用下进入生物体内, 并以植硅体(phytolith)、蛋白石(opal)等生物硅形式存在(Sangster *et al*, 1986; Ragueneau *et al*, 2000) (图 1)。硅的生物或非生物循环在不同时间尺度上与全球碳循环紧密相关。

## 1.2 植硅体

De Saussure (1804)在植物中发现硅的成分, 至此, 植物可以从土壤中吸收硅的机理慢慢被认识。陆地生态系统中, 植物生长过程中吸收土壤中的可溶性硅, 在植物根、茎、叶系统细胞内、细胞壁或细胞组织之间生成的非晶质无定形二氧化硅( $\text{SiO}_2$ )颗粒(Kaufman *et al*, 1981; Song *et al*, 2012), 即植硅体, 也称植物蛋白石。在大多数植物体内, 90%以上的  $\text{SiO}_2$  以植硅体的形式沉积(王永吉等, 1993)。因植硅体具有抗分解、耐腐蚀、抗氧化等特性, 使植硅体在植物死亡和腐烂之后由细胞中脱离出来, 能够长期保存于土壤及沉积物中(Parr *et al*, 2010; Song *et al*, 2016), 其在土壤或沉积层的平均周转时间可达数百年甚至千

年(Alexandre *et al*, 2012)。由于植硅体比重大, 多为原地沉积埋藏, 因而前期较多用于古植被重建(Delhon *et al*, 2003)、古气候学研究(Abrantes, 2003)、古环境重建(Lu *et al*, 2006)和植硅体放射性定年(Piperno, 2016)等。

植物在形成植硅体的过程中会包裹 1%~6%的有机碳, 即植硅体碳。由于受到植硅体的保护, 这部分碳在植物分解后仍可长期保存在土壤中, 随着时间累积和周转, 这部分碳或可以在千年乃至万年尺度上保存在土壤或沉积物中而形成稳定的有机碳库。如 Wilding (1967)利用  $^{14}\text{C}$  定年技术发现, 沉积层中的植硅体碳可追溯至 13 300 年前, 对纳姆度地区的火山灰和古土壤层中的植硅体碳的研究也发现, 这部分封存的碳被保存了至少 8 000 年(Parr *et al*, 2005), 甚至在第三纪以及白垩纪的沉积层中亦有发现植硅体碳的存在(Strömberg, 2004)。与 2000 年相比, 植硅体碳所占土壤碳的比例也由 10%升至 82% (Zuo *et al*, 2011)。因此, 植硅体碳被认为是相对稳定且不易分解的碳库, 成为陆地生态系统碳库的重要组成部分(Parr *et al*, 2005), 作为一种长期稳定的生物地球化学碳汇机制引起人们的重视(Parr *et al*, 2005; Song *et al*, 2016), 植硅体的固碳潜力成为现今陆地生态系统固碳机制研究的热点(Parr *et al*, 2011; Song *et al*, 2012、2016; Zuo *et al*, 2014; Qi *et al*, 2017), 植硅体碳汇成为新的碳汇方式。

植硅体存在于大多数陆地植物中, 但不同植被植硅体含量存在差异, 故不同植物植硅体封存的碳量也存在很大差异(Parr *et al*, 2010; Song *et al*, 2012; Li *et al*, 2013a、b)。最初 Parr 等(2010)认为, 只能通过筛选高植硅体碳含量植物来提升陆地碳汇。而 Li 等(2013b)提出通过合理施用硅肥应可以在提高水稻产量的同时提高生态系统植硅体碳汇潜力。Guo 等(2015)在盆栽试验水稻中施用硅肥(岩粉)验证了这一观点。Song 等(2015)对稻田施用额外的钢渣硅肥亦证明这一现象。Zhao 等(2016)则通过对内蒙古退化草地施加氮肥显著提高了该退化草地植物的植硅体碳产生通量。因此, 目前许多研究开始关注如何通过不同方式来提升生态系统的植硅体碳汇潜力。例如, 通过合理扩大高植硅体作物如水稻(*Oryza sativa*)、小麦(*Triticum aestivum* L.)、甘蔗(*Saccharum*)等的面积及对稻田施用生物质炭、富含硅的有机肥等额外硅肥来提高农田生态系统植硅体碳汇潜力(Parr *et al*, 2011; Li *et al*, 2013b; Sun *et al*, 2016), 以及通过避免过度放牧、恢复退化草地和施肥等手段提高草地净初级生产力来

提高草地系统植硅体碳汇量等。Parr 等(2005)指出, 如果将全球潜在耕地都通过竹林造林或再造林, 全球植硅体碳封存量可达到当前大气 CO<sub>2</sub> 排放量的 11%。由此可见, 植硅体碳汇可作为一种高效的碳汇机制途径, 硅在陆地生态系统的碳汇功能中发挥着重要作用。

### 1.3 生物硅

生物硅(BSi)是一种无定形硅, 也被称为生物蛋白石或蛋白石(Conley, 1998), 由不同生物来源的不同组分组成, 如硅藻、放射虫(Radiozoa)、海绵骨针等, 而硅质藻类的硅质外壳是其最主要来源(Conley *et al.*, 1993), 海洋硅藻是 BSi 最主要的生产者。在海洋生态系统中, 硅藻作为一种单细胞浮游植物, 通过光合作用吸收 CO<sub>2</sub> 合成自身有机质, 贡献了约 40% 的海洋初级生产力, 在富含营养盐的近岸海域, 硅藻生产力甚至可占初级生产力的约 75% (Nelson *et al.*, 1995)。硅藻吸收利用 DSi 将溶解态硅转化为颗粒态 BSi, 随之沉降到海底并埋藏。因此, 沉积物中 BSi 也可用来表征不同历史时期水体富营养化及上层水体初级生产力状况。以硅藻代谢为主导的硅酸盐泵(Dugdale *et al.*, 1995)吸收 DSi 的同时, 将合成的有机碳打包在 BSi 颗粒中, 使碳从上层海洋输送至深层海洋, 通过硅藻繁殖与沉降埋藏的碳量可占海洋碳埋藏量的 40% (Tréguer *et al.*, 2018), 因此, 参与调节大气-海洋 CO<sub>2</sub>。海洋对大气 CO<sub>2</sub> 的调节主要通过溶解度泵和生物泵实现, 溶解度泵以物理过程为动力, 生物泵则由上层海洋各类浮游植物代谢活动所驱动。因而, 硅藻通过吸收、代谢和转换陆源输入的溶解态硅, 将硅循环和碳循环紧密相连, 硅藻成为硅循环和碳循环耦合的重要媒介, 对海洋生物泵的启动以及连续性具有重要作用(Ragueneau *et al.*, 2010)。海洋中的硅和碳通过始于小分子尺度并扩展至可能的最大时间和空间尺度的相互作用建立起了密切的耦合作用(Ragueneau *et al.*, 2006b)。

硅藻利用海水中 DSi 形成坚硬的硅质外壳, 该外壳沉降速率快、降解速率慢, 对于生物泵(biological bump)的效率和碳从海表输入至深层海洋的埋藏过程至关重要(Alldredge *et al.*, 1989、1988)。硅质浮游生物死亡后, 硅质介壳开始溶解, 即开始了以 BSi 溶解为途径的 DSi 的再生过程。Tréguer 等(2013)在对全球硅循环进行估算时指出, 真光层产生的 BSi 约有 56% 会在真光层溶解, 约 33% 可到达沉积物-水界面, 仅约 2.6% 最终被埋藏(图 1), 沉积物-水界面 BSi 溶解释放的 DSi 的量约占真光层产生 BSi 的 30%。由此可

见, 再生的 DSi 又成为水体 DSi 的来源维持上层海洋硅藻生产力(Nelson *et al.*, 1995)。如美国马萨诸塞州波士顿港底部再生的 DSi 占浮游植物生长所需 DSi 的 60% (Giblin *et al.*, 1997)。Liu 等(2002)在黄海的研究发现, 沉积物-水界面 DSi 扩散贡献量可占该海域 DSi 来源的 84%。然而, 颗粒物的沉积速率会影响沉积物-水界面附近 BSi 的保存。通过对近岸营养状况和藻华的研究发现, 较高的氮、磷输入促进硅藻碳生物量增加, 引起硅藻沉降速率增加, 导致硅藻在底层沉积物中的埋藏量增加(Officer *et al.*, 1980)。Ragueneau 等(2002)也指出, BSi 沉积速率越高, 埋藏效率也随之升高。如在沉积速率高达 250 cm/ka 的海区, BSi 埋藏效率高达 86%, 而当沉积速率 < 2 cm/ka 时, BSi 的保存效率几近为 0 (DeMaster *et al.*, 1996)。硅藻的大小、形态和元素组成存在很大差异, 但这些因素又控制着生源物质的数量、质量和沉降速度(Tréguer *et al.*, 2018)。此外, 近岸生态系统中 Si/N、Si/P 值的降低也会导致浮游植物群落中硅藻数量减少进而限制硅藻的硅碳生产和输出。

硅酸盐是硅藻生长和繁殖必须的营养物质, 调控硅藻的生长和代谢, 其浓度决定了硅藻群落的稳定性和持续时间(Karasiewicz *et al.*, 2018), 进而也会影响海洋的固碳能力(Tréguer *et al.*, 2018)。基于此, 20 世纪下半叶开始, 硅循环在海洋生化循环和碳埋藏中的关键作用开始受到重视(Smetacek, 1998)。随着研究的深入, 科学工作者提出了一系列有关硅藻驱动海洋碳循环的假说, 如“铁假说”(Martin, 1990)、“硅假说”(Harrison, 2000)、“硅溢漏假说”(Brzezinski *et al.*, 2002)等。追溯过去, “硅溢漏假说”作为可能机制之一用于解释冰期/间冰期大气 CO<sub>2</sub> 浓度的变化(Matsumoto *et al.*, 2002)。Tréguer 等(2000)也在评述“硅假说”模型时将其称为“CO<sub>2</sub> 的生物硅控制”。海洋中的生物泵也因此被称为“生物硅泵”。硅藻主导硅循环的同时, 又影响了碳、氮、磷等元素的生物地球化学循环, 对全球营养盐循环和渔业生产至关重要(Endo *et al.*, 2018; Sutton *et al.*, 2018)。

此外, 近年研究证明, 广泛存在于海洋表层水体中的单细胞聚球藻(*Synechococcus*)(一种海洋蓝藻, 在寡营养水域占主导地位)能够积累硅(Baines *et al.*, 2012; Tang *et al.*, 2014; Deng *et al.*, 2015; Ohnemus *et al.*, 2016)。Baines 等(2012)在东赤道太平洋和马尾藻海的研究指出, 聚球藻细胞生物量标准化后的硅硫比和硅磷比, 平均值可达硅藻细胞的 50%。室内培养的聚球藻菌株中同样存在硅积累现象(Baines *et al.*, 2012)。目前, 虽然对聚球藻吸收硅的机理和调控机制尚不清

楚,但其在大洋硅循环中的作用却不容忽视,尤其是寡营养海域(孙军等, 2018),且有研究也表明,其对垂直碳输出具有重要的潜在影响。如在北大西洋的观测数据统计显示,虽然,活体聚球藻含有的生物硅仅占总生物硅的1%~4% (Ohnemus *et al.*, 2016),但真光层聚球藻向深层输出硅的量约占总输出量的11% (Tang *et al.*, 2014)。也有研究表明,聚球藻的碳量输出约占总颗粒碳通量的2%~13% (Lomas *et al.*, 2011; Partensky *et al.*, 1999; Richardson *et al.*, 2007; Stukel *et al.*, 2010; 孙军等, 2018),对颗粒碳的深层输出具有重要意义。Deng 等(2015)研究指出,聚球藻碎屑通过胞外聚合物和溶解有机物形成快速沉降的聚合物(440~660 m/d),其输出碳是单个细胞聚球藻的2~3倍。因而,在大洋中具有较高丰度的聚球藻,对硅的连续积累提供了一种不受硅藻控制的吸收硅的途径(Ohnemus *et al.*, 2016),将成为连接海洋硅循环和碳循环的新桥梁(孙军等, 2018)。

由此可见,硅在生物调控的海洋碳循环中扮演着重要角色。这些研究也充分说明,硅循环和碳循环有着千丝万缕的联系,海洋硅循环与备受关注的CO<sub>2</sub>问题和全球气候变化紧密相关,极大程度上调控着现代海洋的碳源汇格局。

#### 1.4 人类活动对硅循环的影响

频繁的人类活动,严重干扰了硅循环。过去几十年中,已有大量研究揭示了人类活动直接或间接对硅循环的影响,尤其是在河流、河口及近岸海域(Conley *et al.*, 1993; Ittekkot *et al.*, 2000; Laruelle *et al.*, 2009; Yang *et al.*, 2015; Tréguer *et al.*, 2021)。所涉及的过程包括森林砍伐(Conley *et al.*, 2008)、风化和河流径流变化(Bernard *et al.*, 2010)、河流筑坝(Ittekkot *et al.*, 2000; Wang *et al.*, 2018)、河口三角洲沉积(Yang *et al.*, 2015)、富营养化及污染(Liu *et al.*, 2012)等。历史发展进程中,森林变为农田,土地使用方式的改变,改变了岩石的风化速率和强度,减少了土壤中无定形硅(主要是生物硅)的储量,同时,极大地改变了活性硅的入河通量(Struyf *et al.*, 2012; Tréguer *et al.*, 2013)(初期通量增加、后期因风化速率降低通量降低)。过去400年间,农业的快速扩张导致土壤中的硅大量流失,入河硅通量呈现显著升高的现象(Clymans *et al.*, 2011),但战后水坝的大量修建又改变了这一现象(Rosenberg *et al.*, 2000)。众所周知,河流筑坝是对硅向海输送影响最显著,且短时间即会产生明显效应的活动(Tréguer *et al.*, 2021)。水坝的“人工湖效应”(van Bennekom *et al.*, 1981)减弱了水动力条件,水体的平均停留时间增加了3倍

(Vörösmarty *et al.*, 1997),颗粒物快速沉降,约1/3的颗粒物被截留(Vörösmarty *et al.*, 2000),BSi、其他颗粒态硅及易溶解的SiO<sub>2</sub>被滞留,同时,加速了淡水硅藻将DSi转化为BSi并从水体中清除的进程(Wisser *et al.*, 2010),增强了硅在河流上游的消耗及埋藏(Maavara *et al.*, 2014),硅的跨区输送被延缓,引起河流下游DSi浓度及入海硅通量的显著降低(Tréguer *et al.*, 2013),切断了下游硅的重要来源(Humborg *et al.*, 1997; Conley, 2002; Dürr *et al.*, 2011)。如铁门大坝建成后,造成多瑙河向黑海输送的DSi浓度降低约60%,通量下降60%~70% (Humborg *et al.*, 1997; Ittekkot *et al.*, 2000);我国三峡大坝建成后,输出至东海的Si/N值也降低了约4倍(Gong *et al.*, 2006)。

随着全球气候变暖及水坝的大量修建,引起的硅循环过程的改变将会更加显著(Laruelle *et al.*, 2009)。升温促进近岸海域BSi的溶解而削弱其沉降通量,同时,全球变暖使表层海洋层化作用增强,DSi随深层水向上的输送受到抑制(Tréguer *et al.*, 2021),上层海洋DSi浓度降低引起BSi生成量及沉降通量的减少,必然引起与之相关的有机碳沉降和埋藏发生变化。水坝修建会进一步降低下游河流及河口DSi的浓度,同时伴随河流及河口区10%~30%的BSi储量削减和河口/近岸沉积物中BSi沉积量的降低,河流输入的硅通量(图1)将会继续降低。

此外,其他人类活动也会改变硅的生物地球化学循环,值得关注并量化(Ragueneau *et al.*, 2010),滤食性动物的滤食和生物沉积作用便是其中之一(Ragueneau *et al.*, 2005),因其导致的局部生物沉积速率显著高于物理沉积速率。硅元素不参与滤食性动物的新陈代谢而随粪便或假粪排出体外(Norkko *et al.*, 2001),导致BSi在沉积物中的滞留,生物沉积的增加可能导致陆海交互作用区域硅元素停留时间的增强(Ragueneau *et al.*, 2005)。

同时,土地使用方式的改变、化石和生物燃料的燃烧、磷矿的开采及由大气中固定氮(Vitousek *et al.*, 1997; Galloway, 1998; Smil, 2000; Rockstrom *et al.*, 2009)等人类活动导致生物圈可利用氮量翻番(Galloway *et al.*, 2003)、地球上移动磷的量增加了2倍(Smil, 2000)。因农业输送至近岸海域的磷酸盐、硝酸盐的量增加了一倍(Meybeck, 1998),而硅酸盐输送量变化不大,使DSi被大量消耗,DSi含量降低,BSi含量升高,水体Si/N、Si/P值减小,硅限制发生的可能性增加,海洋硅限制问题因而日益凸显,DSi限制初级生产力逐渐成为近岸海域的一个共同特征(Turner

*et al*, 1998)。过剩的氮、磷则促进了非硅质浮游植物如甲藻(Dinophyta)的生长(Tréguer *et al*, 2013), 也引起浮游植物群落由硅藻向非硅质藻类转变(Beucher *et al*, 2004), 硅藻在近岸生态系统中的相对重要性降低(Humborg *et al*, 2000)。这也是引起近岸海域非硅藻类有害藻华暴发的原因之一(Yang *et al*, 2018)。

河流 Si/N、Si/P 值的长期下降, 以及近岸海域由氮限制逐渐向硅限制变化(Fransz *et al*, 1985; Ragueneau *et al*, 1994、2010), 引发浮游植物群落组成和食物网改变(Li M T *et al*, 2016)的现象, 业已在很多近岸生态系统中观测到(Turner *et al*, 1998、2008; Zhang *et al*, 2020)。如人类活动引起多瑙河氮、磷输入量的增加, 富营养化及大坝建设引起的 DSi 含量的降低, Si/N 值减小, 使得黑海浮游植物主要类群由硅藻向非硅质类浮游植物演替(Humborg *et al*, 1997; Yunev *et al*, 2007)。我国渤海也因人类活动导致陆源氮输入增加, 由氮限制转变为磷限制和硅限制(Wang *et al*, 2019)。硅限制的出现会引起海洋内部碳输送量的减少(Sieracki *et al*, 1993; Dugdale *et al*, 1995)。由于河流输入引起营养元素过多地向海洋排放, 造成近岸海域严重的富营养化和赤潮, 近而引发缺氧, 也会影响河口和近海固碳/储碳量, 使高生产力河口和近海成为 CO<sub>2</sub> 的源(Jiao *et al*, 2018)。

人类活动直接干扰影响了陆源物质向海运输的迁移转化过程, 近岸海域在陆源物质通过河流向开放海域输运的过程中扮演了“过滤器”的角色, 大量溶解态、颗粒态物质在这一区域被吸收利用或沉降埋藏而截留(Billen *et al*, 1991; Ragueneau *et al*, 2010)。早在 21 世纪初, DeMaster (2002)认为, 近岸海域作为 BSi 的汇被大大低估。因而连接陆地与海洋两大生态系统的近岸海域, 成为受人类活动影响最为剧烈且物质丰富的区域, 虽然, 其面积仅占全球海洋面积的 7%, 但对全球海洋初级生产力的贡献高达 30% (Gattuso *et al*, 1998; Bauer *et al*, 2013), 其中硅藻对初级生产的贡献高达 58% (张周凌, 2019), 埋藏了超过 80% 的海洋有机质, 同时支撑着全球 90% 的捕鱼量, 在全球碳的输出和埋藏中起着至关重要的作用(Hedges *et al*, 1995; Rabouille *et al*, 2001)。但自 20 世纪 80 年代, 全球范围内近岸海域观测到硅酸盐浓度大幅降低(Ragueneau *et al*, 2006a), 极大地影响近岸海域硅藻的生长和分布, 对全球固碳产生显著影响。在长时间和空间尺度上, 沿岸生态系统向外海输送硅的量同样对海洋活性硅及生物泵的大小和全球气候产生影响(Ragueneau *et al*, 2006b)。

## 2 近海贝类养殖生态系统硅碳循环耦合机制

### 2.1 硅在贝类养殖碳汇形成中的作用

海水养殖作为重要的潜在蛋白质源, 可缓解人口增长产生的巨大食物压力。近几十年, 我国海水养殖业得到迅猛发展, 海水养殖产量占全球海水养殖总产量的 50% 以上(FAO, 2021)。我国海水养殖又以贝类养殖为主, 2020 年贝类养殖产量占海水养殖总产量的 69%, 滤食性贝类产量占到贝类总产量的 90% 以上(农业农村部渔业渔政管理局等, 2021)。贝类养殖产业已成为我国沿海地区经济的重要支柱产业, 也是我国“蓝色农业”的主要内容。

海洋生物固定了全球 55% 的碳, 可有效地缓解温室气体排放对全球气候变化的影响(唐启升等, 2016)。渔业生产活动则促进了水生生物吸收水体中的 CO<sub>2</sub>, 并通过收获将转化为生物产品的碳移出水体, 形成“可移出的碳汇”, 提高了养殖水域生态系统吸收大气 CO<sub>2</sub> 的能力(唐启升, 2010)。因此, 唐启升院士在 2010 年提出了“渔业碳汇”的概念(唐启升, 2010), 并将不需投放饵料即能收获水产品的渔业活动称为碳汇渔业(唐启升等, 2016), 包括藻类养殖、滤食性贝类养殖、增殖渔业、捕捞渔业等(唐启升等, 2022)。据估测, 我国海洋渔业和水产养殖的固碳量有望实现达到每年 10% 的碳减排量(唐启升, 2010)。因而, 在我国争取 2060 年实现碳中和这一宏伟目标下, 海水养殖活动除为人类提供不断增长的营养和食物需求(Lubchenco *et al*, 2020)外, 作为碳汇及碳增汇途径业已成为研究的重点(唐启升等, 2013), 探求其增汇机制也成为重要工作实践。

滤食性贝类作为我国贝类的主要养殖对象, 在生长过程中, 通过大量滤食水体中浮游植物和碎屑摄取水体中悬浮颗粒有机碳促进软体组织生长, 在外壳形成过程中, 可直接吸收水体中无机碳(唐启升等, 2016)。由于无需投放饵料, 没有额外碳添加, 贝类个体释放的 CO<sub>2</sub> 在自系统中也会被浮游植物再次吸收利用(唐启升等, 2022), 产生了大量吸收使用水体中碳元素的效应, 成为重要的渔业碳汇。因此, 根据贝类养殖活动中物质迁移转化的途径, 可将贝类养殖中的碳汇划分为使用碳、移出碳、储存碳和释放碳 4 个储库(唐启升等, 2022)。其中, 使用碳即为贝类个体通过滤食大量使用以浮游植物为主的颗粒有机碳以及贝壳形成过程中使用的碳, 亦可称之为总碳汇(唐启升等, 2022)。2018—2020 年贝类平均使用碳量达到 547 万 t/年, 约等于每年义务造林 73 万 hm<sup>2</sup>, 贝类养殖通过滤食



颗粒有机碳大量使用了  $\text{CO}_2$ , 发挥了滤食性贝类的增汇作用(唐启升等, 2022)。因而, 关于贝类养殖碳汇的过程机制、原理和增汇途径成为重要的科研探索领域。

作为使用碳来源之一, 浮游植物是滤食性贝类的主要物质来源(Kang *et al.*, 2006), 胶州湾每年约有30%的浮游植物被贝类所消耗(Han *et al.*, 2017), 浮游植物对胶州湾潮间带双壳贝类碳库的贡献高达86%~89%(Xu *et al.*, 2007)。但贝类对浮游植物的滤食又具有选择性, 以滤食  $3\ \mu\text{m}$  以上颗粒物为主(Newell, 2004), 其中硅藻成为滤食性贝类最重要的饵料来源(Pernet *et al.*, 2012; Jiang *et al.*, 2019)。硅藻通过光合作用将水体中  $\text{CO}_2$  转化为有机碳, 同时吸收硅酸盐构建其自身结构(图2)。滤食性贝类通过滤食硅藻, 将一部分生源要素同化用于自身生长, 部分硅藻光合作用固定的碳转化为贝类养殖碳汇, 而贝类呼吸等代谢过程和钙化过程释放的  $\text{CO}_2$  也会被浮游植物再次吸收(图2)(唐启升等, 2022; 姜妮妮等, 2022)。贝类养殖活动对硅藻驱动的生物碳泵起到了“分流”的作用,

改变了水体中碳循环路径和生物泵效率。贝类超强的滤食作用也会改变浮游植物群落结构, 对浮游植物产生下行控制效应(Jacobs *et al.*, 2015; Jiang *et al.*, 2019), 如胶州湾菲律宾蛤仔(*Ruditapes philippinarum*)养殖导致浮游植物周转率降低(姜妮妮等, 2022)。

贝类养殖碳汇功能的充分发挥与浮游植物的种类、数量及周转率相关, 当浮游植物生长受到限制会对浮游植物的固碳作用产生影响外, 硅藻作为贝类食物来源, 又会反过来限制养殖水域的贝类养殖容量, 对贝类生长产生上行控制作用(Chauvaud *et al.*, 1998)。硅酸盐是硅藻生长和繁殖必须的营养物质(Kilham *et al.*, 1988; Officer *et al.*, 1980), 调控硅藻的生长和代谢。由此可见, 硅藻作为物质来源将贝类养殖碳汇和硅循环紧密联系起来, 硅元素在驱动贝类养殖碳汇形成过程中将扮演重要的角色, 贝类养殖也会对水体硅-碳耦合过程产生影响。因此, 可通过研究贝类养殖水域硅藻产量与组成的调控因子和机制及硅-碳耦合机制来探讨贝类养殖碳汇的增汇潜力和途径。

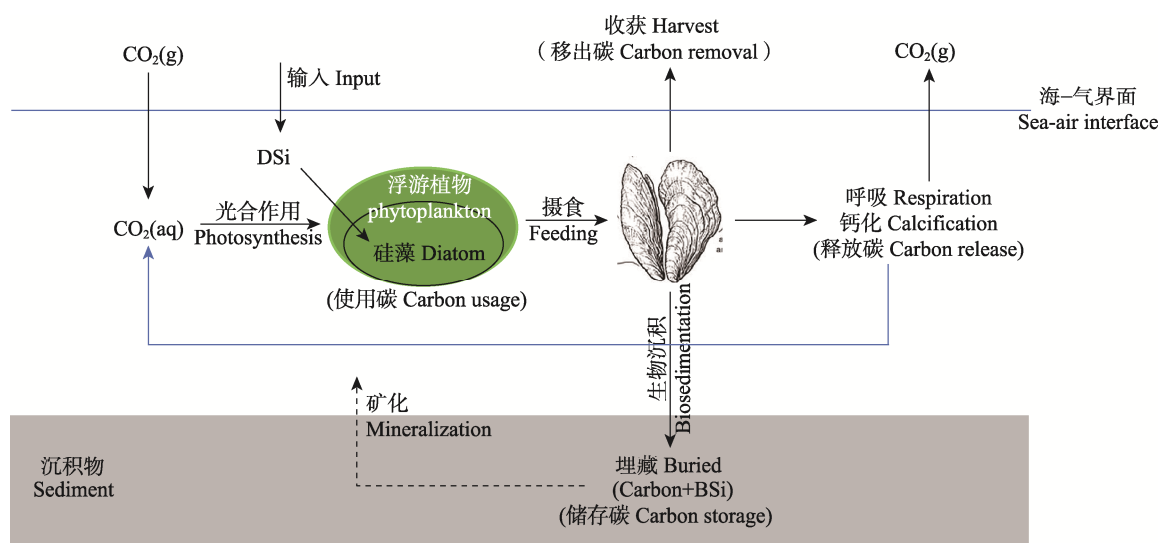


图2 滤食性贝类生长过程中对碳、硅酸盐的利用

Fig.2 The utilization of carbon and DSi by filter-feeding shellfish

根据唐启升等(2016、2022)和蒋增杰等(2022)整理。

The figure was plotted according to Tang *et al.* (2016, 2022) and Jiang *et al.* (2022).

对于一些海洋生态系统, 特别是近岸生态系统, 硅输入的改变可显著影响初级生产者的群落组成, 尤其是硅藻和非硅质浮游植物之间的生产平衡(Harrison, 2000; Losic *et al.*, 2009)。如在末次盛冰期, 因大气沉降输入硅的量的增加使得硅藻对海洋浮游植物生物量的贡献高达79%, 显著高于现今水平(54%)(Tréguer *et al.*, 2000)。陆源输入影响渤海水体由氮限制逐渐转

变为磷限制和硅限制, 营养盐结构和生态环境发生显著变化(Wang *et al.*, 2019), 长江口优势种也由硅藻转变为非硅质类植物(Li M T *et al.*, 2016)。对于半封闭的养殖海湾, 陆源输入是硅酸盐的主要来源, 由于人类活动引起的氮磷输入的增加以及河流硅输送量的减少, 贝类养殖排泄引起的无机氮、磷酸盐含量的升高而引起硅的消耗, 均会增加硅限制发生的风险。硅限

制现象在典型养殖海湾也已陆续观测到。如獐子岛虾夷扇贝(*Patinopecten yessoensis*)养殖区春季枯水期,硅限制出现的频率和程度显著高于非养殖区(Liang *et al*, 2019);莱州湾枯水期出现硅限制现象(由丽萍等, 2021)。陆源输入是桑沟湾硅酸盐的主要来源,春季枯水期在桑沟湾已观测到硅限制现象出现(Li R H *et al*, 2016)。硅匮乏的现象日益凸显,必然对以硅藻为基础的近海贝类养殖生态系统产生深远影响,最终对海洋的固碳能力(Tréguer *et al*, 2018)和贝类养殖碳汇产生影响。

硅的缺乏常常会造成甲藻类取代硅藻成为优势种(Davidson *et al*, 2012),可以直接影响以硅藻作为主要食物来源的贝类、滤食性鱼类、浮游动物等。胶州湾已由 20 世 60 年代的氮限制为主逐渐转变为现今的硅限制,营养盐限制的改变导致藻类优势种的变化,最终将影响胶州湾内的生态结构和渔业生产(贾守伟等, 2015)。因此,硅酸盐匮乏,也会导致经由硅藻进入贝类养殖碳汇的碳量削减。Wassmann 等(1996)提议,人工添加硅酸盐供给促进硅藻增殖以促进初级生产和生物泵,并尝试了在围隔实验中,向硅酸盐相对缺乏的水体直接添加硅酸盐来缓解硅限制,但在天然海域很难控制其添加量及控制对生态系统带入的其他影响。焦念志等(2021)指出,人为添加橄榄石矿物可整合  $\text{CO}_2$ ,同时,释放的硅酸盐利于硅藻生长,或可有效地促进水体  $\text{CO}_2$  的吸收。将在农业中广泛应用的稻壳灰作为硅酸盐肥料在海水中施用(吕静静等, 2019; 张凯等, 2024),以缓解水体硅限制,同时,对水体环境较为友好,但也存在硅酸盐释放率低及投放量的限制。因而,在硅相对匮乏或较低的养殖海域,通过人为添加来提高水体硅酸盐浓度而促进硅藻生长进而提升贝类养殖使用碳来源,在缓解硅缺乏/限制、维持初级生产的同时或可成为提升贝类养殖碳汇的手段。

## 2.2 贝类养殖对硅迁移转化过程的影响

养殖贝类对营养盐的调控主要有 2 个途径:一是通过摄食浮游植物及自身生长达到对水体中营养盐的消耗;二是通过排泄/生物沉积作用影响营养盐的消耗和再生。滤食性贝类通过滤食水体中浮游植物或碎屑,将一部分生源要素同化转化用于贝类生长并最终通过贝类收获而移出水体,间接加速了对营养盐的消耗,尤其是对再生速率较慢的硅酸盐的消耗(Richard *et al*, 2007)而削弱了硅的可利用性;其余部分以无机营养盐形态排泄至水体或以粪便/假粪被排出后(秦培兵等, 2001),通过生物沉积作用输入底泥

沉积物中而导致硅的埋藏、增强了硅的移除(Ray *et al*, 2021)。但也有研究指出,贝类养殖提高了养殖区沉积物硅的交换通量(Green *et al*, 2013),促进了沉积物中营养盐的再循环速率和有机质的可利用性(Ray *et al*, 2020)。

贝类排泄释放的无机态氮、磷,可能成为重要的营养物质来源,如在新西兰 Mahurangi 港,江珧(*Atrina zelandica*)排泄释放大量铵盐,对初级生产的贡献可达 80%(Gibbs *et al*, 2005),Oosterschelde 河口区紫贻贝(*Mytilus edulis*)代谢的磷酸盐占再生磷酸盐的 31%~85%(Prins *et al*, 1994)。但贝类几乎不排泄释放硅酸盐, Ray 等(2020)对全球牡蛎(*Ostreidae*)研究进行统计时也指出,没有关于牡蛎排泄释放硅酸盐的相关研究结果。因而排泄释放的无机氮磷则会促进硅藻对硅酸盐的消耗,进而加速水体硅酸盐的消耗,从而提升硅限制发生的风险。

贝类产生的粪便或假粪通过生物沉积作用输入底泥沉积物的过程,生物沉降的沉降速率快于原悬浮颗粒(Fenchel, 1991),因而多数水产养殖都会使养殖区沉降速率增高(Hatcher *et al*, 1994; Dobson *et al*, 1998),在水动力条件差的水域尤为明显(Grant *et al*, 2005)。Verwey (1954)也曾指出,贝类在水层耦合中起到关键作用,因其将未消化物质以粪便或假粪的形式排出,沉降至沉积物表面,可能引起养殖区或邻近水域有机质的累积,即把海洋中营养物质富集到局部养殖区。Hatcher 等(1994)在加拿大 Upper South Cave 的研究发现,贻贝(*Mytilidae*)区生物沉降速率是非养殖区的 2 倍多。硅藻利用的硅中有近 70%在其硅质外壳中,但贝类滤食浮游植物并不能利用硅质外壳中的硅,而是保留有机物并以粪便/假粪的形式将硅直接排出体外(Kido *et al*, 1975)。Ragueneau 等(2002)也指出,硅藻摄食者基本不需要营养物质硅(Tande *et al*, 1985),因而这部分通过生物碳泵形成的 BSi 经贝类滤食后通过生物沉积作用会进入底泥沉积物中(图 2)。BSi 的埋藏是海洋硅的主要移除方式,沉积速率越高,BSi 的埋藏效率也高(Ragueneau *et al*, 2000)。Pouvreau (1999)对 10 种软体动物进行研究时发现,约 46%被摄入的碳以粪便或假粪的形式被排出,但摄食的 BSi 则全部通过粪便排出,导致 Si/C 值大幅升高,因而随 BSi 沉降埋藏的碳量也将随之发生改变。Brest Bay 中角毛藻(*Chaetoceros*)的 Si/C 值为 0.05,滤食其的大西洋螺粪便中的 Si/C 值变为 0.12,表明经大西洋螺滤食后出现了硅碳的解耦现象,也使 Si 加速向沉积物传递积累,造成相当大部分 BSi 被埋藏而脱离硅循环,形成硅的缺乏(Ragueneau *et al*, 2005)。贝类滤食



改变了经典食物链中初级生产者物质循环的途径,被贝类滤食消化以真、假粪便的形式更多的进入底栖食物链。但贝类产生的真、假粪便中营养元素的循环速率存在一定差异,如 van Broekhoven 等(2014)研究发现,腐解贻贝粪便中具有较高的硅酸盐再生速率。而且贝类生物的消化过程可去除硅藻外层起保护作用的有机质外壳,对 BSi 的溶解产生显著影响,也可加速硅酸盐的再生,贝类养殖影响下可能出现增强的“硅酸盐泵”的作用,如入侵的大西洋舟螺(*Crepidula fornicata* Linnaeus)通过增加生物沉积,产生一个活跃的硅酸盐泵,又促进了水体营养盐的消耗(Ragueneau *et al.*, 2002)。Jansen 等(2012)指出,贻贝生物沉积中硅的矿化速率因食物来源不同,导致3月硅的释放量较8月和11月高60~80倍。

贝类的生物沉积也加速了碳、氮、磷的沉积,使得有机质在沉积物中富集,较非养殖区有机碳、氮含量更丰富(Jiang *et al.*, 2019; Ysebaert *et al.*, 2002)。沉积物中有机质的增加,促进了微生物代谢活动,加快了有机质的矿化分解速率,进而也加快了营养盐的释放速率(Newell, 2004),促进营养盐的循环。由此可见,贝类养殖除对生物碳泵有分流作用外,也改变了 BSi 的沉降路径,颗粒物沉积速率的增加可能加速 BSi 的埋藏,提高硅在这一生态系统中的保存效率,促进硅的移除而造成水体硅的亏损,最终可能也促进了硅碳的解耦,随着 BSi 沉降向底层水体输送的碳通量也会受到影响,初级生产者的物质循环途径发生改变,生态系统中的硅碳耦合过程也随之发生变化。但也可能出现增强的硅酸盐泵,具体情况则可能跟养殖海域水体深度和沉积环境有关,需具体深入分析。

作为我国典型的多营养层次综合养殖海湾,牡蛎、扇贝等是桑沟湾的主要养殖贝类(Jiang *et al.*, 2015)。桑沟湾的养殖模式不仅促进了生态系统的高效产出,同时也挖掘了碳汇扩增的生态服务功能。在人类活动影响下,桑沟湾水体营养盐结构逐渐发生改变。由于河流径流携带大量硝酸盐,河流输入的 Si/N 值(摩尔比为 1:3.7)显著偏离 Redfield 比值(1:1) (Li R H *et al.*, 2016)。自 20 世纪 80 年代筏式养殖开始,桑沟湾水体 Si/N 值发生明显变化,逐渐偏离 Redfield 比值, Si/N 值的这种长期变化可能与湾内贝类养殖及陆源输入有关。在季节尺度上,主要受陆源输入影响,硅酸盐夏季最高,春季最低,已呈现潜在硅限制现象(孙珊等, 2010; Li R H *et al.*, 2016),近年春季硅限制现象更加显著(张凯等, 2024)。虽然,目前桑沟湾浮游植物仍以硅藻为主,但开展大规模养殖后,湾内已逐渐出现浮游植物物种数下降、优势种类发生改变、

多样性指数降低(李超伦等, 2010; 傅明珠等, 2013; 钱罡等, 2017)等现象,均对群落结构稳定性产生影响,浮游植物生物量季节格局也发生了变化(慕建东等, 2009)。湾内贝类养殖区沉积速率达到 2.08 cm/yr (白怀宇等, 2022),明显高于湾口藻类养殖区(0.59~0.73 cm/yr) (刘赛等, 2014),且远高于黄海和东海等海域(杨茜等, 2010)。较高的沉积速率,也会加速 BSi 和碳向沉积物的输运。在此情况下,桑沟湾硅的生物地球化学过程的改变及硅缺乏会对水体碳循环产生何种影响,硅循环与碳循环的耦合过程发生何种改变,是否影响贝类产值及贝类养殖碳汇,值得我们进行深入研究和探讨。

### 3 展望

人类活动使营养盐浓度增大的同时改变了营养盐结构,因氮、磷输入增大而硅酸盐的浓度相对不变甚至降低,世界各大河口、海湾逐渐出现硅限制现象(Justić *et al.*, 1995; Turner *et al.*, 1998)。我国北方典型的养殖海湾獐子岛(Liang *et al.*, 2019)、莱州湾(由丽萍等, 2021)、胶州湾(Shen, 2001; 贾守伟等, 2015)以及桑沟湾(Li *et al.*, 2016; 张凯等, 2024)在春季也均出现了硅限制现象。另外,硅酸盐浓度通常作为常量营养盐研究中的辅助数据,更多的研究着重于讨论氮、磷行为及二者的比值,现代养殖海湾硅循环和碳循环相互作用的相关研究并不多见,硅匮乏引起硅藻群落结构改变及对贝类容量和碳汇的影响更是研究甚少。在国家“双碳”战略背景下,研发渔业碳汇增汇途径是亟需解决的问题(蒋增杰等, 2022)。因此,在这一目标引领下,我们从硅元素的视角探究其在滤食性贝类碳汇形成过程中的作用,积极探索贝类养殖碳汇扩增的新途径。

针对此情况,围绕硅-碳耦合过程,选择在典型多营养层次综合养殖海湾开展系统全面的现场观测及受控培养实验,剖析硅的调控机制、厘清硅的源汇收支,量化硅的各个储库及周转速率,解析贝类养殖活动影响下硅的关键生物地球化学过程及硅-碳耦合机制,进而评估硅在贝类养殖碳汇中的作用,以期缓解养殖海湾开始显现的硅缺乏情况及挖掘贝类养殖碳汇扩增途径和潜力提供思路,期望为促进海洋碳增汇与生态系统可持续发展提供数据参考和科学支撑。

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## The Biogeochemical Cycle of Silicon and Its Role During the Formation of an Aquaculture Carbon Sink

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**Abstract** In the context of global climate change, one central interest is an improved understanding of the global carbon cycle. A large number of studies have investigated carbon cycling and associated elements, mainly nitrogen and phosphorus. However, as an essential element for diatom growth, Si has been largely ignored. Si is the second most abundant element and is widely distributed on Earth. The chemical weathering of silicates on land and photosynthesis of diatoms in the ocean play an important role in atmospheric CO<sub>2</sub> levels at various timescales. Diatoms are the primary producers in the ocean and account for as much as 40% of the annual ocean carbon fixation, which have an absolute requirement for Si to form siliceous cells. The main mechanism underlying ocean carbon sinks is a “biological pump.” The biological pump is driven by the biological Si pump to a large extent. Therefore, the biogeochemical process of Si has become one of the key research issues for global environmental change.

Based on previous studies, the regulation and influence of the Si biogeochemical cycle on the carbon cycle are discussed in this review. The coupling effect and mechanism of the Si and carbon cycles in shellfish culture ecosystems were analyzed and the key research questions were explored. Chemical weathering of silicates and the cycling of their products form the basis of Si biogeochemistry. CO<sub>2</sub> is consumed during weathering reactions. Therefore, silicate weathering on land represents an important sink for atmospheric CO<sub>2</sub>. Furthermore, at the geological timescale, primary silicate mineral weathering is the source of secondary silicate. Terrestrial plants absorb soluble silica through their root system during growth. Amorphous silica deposited in plant tissue after maturity is called phytolith. Phytoliths have excellent geochemical stability and occlude a certain amount of organic carbon during the formation process. The organic carbon occluded within phytolith is called phytolith-occluded carbon (PhytOC) and is buried in the soil. PhytOC is released into the soil with phytolith and may be preserved in soils for several thousands of years. As a consequence, PhytOC in terrestrial ecosystems could be significant potential carbon sinks globally due to the refractory phytolith. Primarily through river input, the dissolved silicate (DSi) is

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transported into the coastal ocean (approximately 84% of DSi input to the oceans). As the major primary producer, diatoms absorb DSi during growth and account for a large fraction of the total carbon fixation in the modern oceans. DSi is converted into biogenic silica via biological processes, is transported to the deep ocean, and is finally buried into sediments with organic carbon in the marine ecosystem. Thus, by controlling the contribution of diatoms to the total primary production, DSi can affect the carbon cycle in oceans. The carbon pump is driven by the Si pump.

Mariculture has developed quickly in recent decades. Shellfish, which are dominated by filter-feeding species, are the main mariculture species. The filter-feeding shellfish consume particulate organic carbon as phytoplankton and use dissolved inorganic carbon to build their shell during growth. Filter-feeding shellfish are an import fishery carbon sink. As one of the important feed sources of filter-feeding shellfish, diatoms form fishery carbon sinks in coastal shellfish culture areas. Silicate is an essential salt for diatom growth. Consequently, the carbon sink of filter-feeding shellfish culture is connected with DSi through diatoms. Si could play an important role in driving the formation of carbon sinks in filter-feeding shellfish culture. Hence, it is necessary to consider all processes and coupling effects in the study of the Si biogeochemical cycle. It is important to understand its role in the carbon sinks of shellfish culture.

Nowadays, in many systems, human perturbation has resulted in a decline in the ratio of Si:N to 1:1 or less, with severe impacts on the quality and structure of aquatic ecosystems. DSi limitation has been reported in many studies, in both coastal and marine waters. DSi limitation causes shifts from diatoms to non-siliceous algae and is supposedly related to the decreasing export of carbon. A shift from diatoms to other species would enhance the recycling of organic matter in the upper water column because diatoms are very effective in carbon sequestration. DSi limitation has also appeared in some aquaculture bays in China, such as Jiaozhou Bay and Laizhou Bay, in spring. Regarding future directions, it is suggested that more research be conducted on Si biogeochemistry in shellfish culture systems and coupling with the carbon cycle. The subsequent results could evaluate the role of Si in the carbon sink of filter-feeding shellfish culture. Future studies are expected to provide ideas for alleviating Si deficiency in the aquaculture bay and exploring the expansion path in shellfish farming.

**Key words**      Silicon cycle; Diatom; Phytolith; Biogenic silica; Carbon sink; Shellfish culture