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基于生命周期法的养殖海带的碳足迹评估*

孙　威[1]　张继红[1,2①]　吴文广[1]　刘　毅[1]
仲　毅[1]　王新萌[1]　康秦梓[1]

(1. 中国水产科学研究院黄海水产研究所 农业农村部海洋渔业可持续发展重点实验室　山东　青岛　266071;
2. 青岛海洋科学与技术试点国家实验室海洋渔业科学与食物产出过程功能实验室　山东　青岛　266071)

摘要　碳足迹是指商品或服务在生产、运输、使用、处置的整个生命周期内排放的温室气体总量。为探究海带(*Saccharina japonica*)在整个养殖周期内 CO_2 的源与汇，本研究基于生命周期评价理论构建了筏式养殖海带碳足迹测算方法，对桑沟湾养殖海带的碳足迹进行了测算，分析了碳足迹的主要影响因素和可能的误差来源。结果显示，养殖 1 t 海带的碳足迹约为–95.93 $kgCO_2e$，其中，碳排放量为 74.30 $kgCO_2e$，碳吸收量为 170.23 $kgCO_2e$。从海带育苗开始至养成收获的整个过程是碳汇过程，其中，以海带生物质碳的形式固定的 CO_2 占比约为 79.9%，以沉积埋藏碳的形式固定的 CO_2 占比约为 14.1%，以惰性溶解有机碳(RDOC)的形式固定的 CO_2 占比约为 6.0%，沉积埋藏碳和惰性溶解有机碳长期封存于深海或海底；养殖设施是主要碳源，碳排放占比为 93.81%，柴油和电能的碳排放占比分别为 5.05%和 1.14%，肥料和运输的碳排放占比仅有万分之一。

关键词　碳足迹；海带；海水养殖；桑沟湾；生命周期法

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近年来，温室气体的过度排放加剧了全球气候变化。我国是第一人口大国，同时，也是温室气体排放第一大国(方琦等, 2021)。为应对气候变化，我国政府郑重提出 CO_2 排放量将在 2030 年左右达到峰值，在 2060 年之前实现“碳中和”的宏伟目标。海洋是地球上最大的活跃碳库，海洋负排放潜力巨大。中国是世界上海水养殖规模和产量最大的国家，然而，就某一项水产养殖产品而言，在其养殖周期内 CO_2 的源汇并不清楚。碳足迹是指商品或服务在生产、运输、使用、处置的整个生命周期内排放的温室气体总量，以 CO_2 当量(CO_2e)表示(Minx *et al*, 2009)。通过开展水产养殖产品的碳足迹评估，不仅能为减排增汇提供科学的理论指导，还能为海洋负排放技术提供具体科学的数据支持，最终可服务于国家碳中和战略(焦念志等, 2021)。

山东省东临黄海北接渤海，海岸线长，海藻养殖行业发达。2020 年全省养殖海藻产量为 66.92 万 t，其中，海带(*Saccharina japonica*)产量为 50.92 万 t，占全省养殖海藻产量的 76%，约占全国海带总产量(165.16 万 t)的 30% (农业农村部渔业渔政管理局等, 2021)。海带在生长过程中能够吸收大量的溶解 CO_2

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① 通信作者：张继红，研究员，E-mail: zhangjh@ysfri.ac.cn

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并将其转化为有机碳，与此同时，海水中 CO_2 浓度降低会加速大气 CO_2 的溶解(张继红等, 2021)。海带同时也是桑沟湾沉积物有机质的主要来源(聂梦晨等, 2022; Sui *et al*, 2019)，这些过程起到了很好的碳汇作用。海带养殖活动又存在大量的物质和能源投入，这些投入会直接或间接释放 CO_2。我们对于获得海带产品的整个养殖生产过程中 CO_2 的源/汇效应并不清楚。为定量分析养殖海带 CO_2 的源汇情况，需要对养殖海带进行碳足迹评估。本研究以山东荣成市桑沟湾为例，基于生命周期评价理论构建了筏式养殖海带碳足迹测算方法，对桑沟湾养殖海带的碳足迹进行计算，分析碳足迹的主要影响因素和可能的误差来源，以期深入了解大型藻类养殖各个阶段的源汇效应，为有针对性的减排增汇技术的建立提供科技支撑。

1　研究方法

1.1　生命周期评价法

本研究基于生命周期评价法(life cycle assessment, LCA) (ISO, 1999)的理论构建了筏式养殖海带碳足迹测算方法。生命周期评价法主要包括目的与范围的确定、清单分析、影响评价和结果解释 4 个步骤。各步骤的具体内容见图 1。

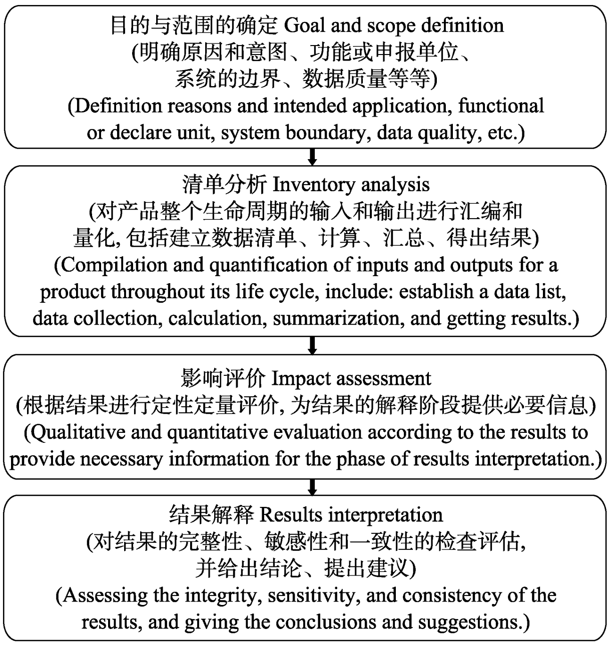

图 1　生命周期评价法的 4 个步骤

Fig.1　Four steps in life cycle assessment

1.2　桑沟湾养殖海带碳足迹评估

1.2.1　目的与范围的确定　　养殖海带作为海域的初级生产者，通过光合作用吸收水体中的无机碳、营养盐等合成有机质，其生长过程可吸收固定碳。海带养殖形成海带产品还包括育苗、养成过程中的用电、用船、养殖设施等释放 CO_2 过程。海带苗为北方海带苗种，以荣成市寻山集团所育之苗为例。北方海带育苗需要低温、流水等条件(张壮志等, 2010)，育苗工作通常在 8 月初开始，在 10 月上、中旬达到出库要求后出库暂养，整个育苗周期约为 70 d，单位苗帘的育苗量为 5 万株/帘。海带成体为山东海区筏式平养法养殖海带，以荣成市桑沟湾为例。海带苗经 15 d 左右暂养达到分苗规格后开始分苗，具体包括剔苗、运苗、夹苗、挂苗 4 步操作。海区平均放苗量为 75 000 株/hm^2 (刘涛, 2019)，平均产量约为 119 t/hm^2，即每养殖 1 t 海带约需 630 株苗。通常 10 月底或 11 月初开始下海挂苗，次年 5—7 月初完成收获，整个养殖周期约为 200 d。

本研究将生产 1 t 海带(湿重)记为养殖海带碳足迹的功能单位。采用从“摇篮到大门”的生命周期法，将养殖海带形成海带产品的整个生命周期划分为育苗期、运输阶段、养成期 3 个阶段。从第 1 天育苗开始到育苗结束为育苗期，海带苗帘由育苗场运输到养殖场为运输阶段，从海上挂苗养殖开始到海带收获上岸为养成期。本研究对于养殖海带碳足迹的计算仅包括 CO_2 一种温室气体，不包含 CH_4 和 N_2O 等其他温室气体。

1.2.2　筏式养殖海带清单分析　　筏式养殖海带清单见图 2。育苗期主要考虑能源和营养盐投入，运输期主要考虑公路运输，养成期主要考虑能源、养殖设施的投入和海带生长过程固定的 CO_2。养殖海带在生长过程中会通过光合作用固定大量的碳，这些碳一部分会以生物质碳的形式存留，一部分会以溶解有机碳(DOC)和颗粒有机碳(POC)的形式释放到海水中(Weigel *et al*, 2021; 尼志杰等, 2022; Jiao *et al*, 2010)。这些 DOC 和 POC 可在“微生物碳泵”作用下转化为惰性溶解有机碳(RDOC)(张永雨等, 2017; Chen *et al*, 2020)或埋藏于海底而形成“长久”碳汇。海带生物质碳、形成的 RDOC 和沉积埋藏碳视为 CO_2 负排放，记为负值。

育苗期的生产投入均采用平均数，育苗期海带苗的生物质碳部分并入养成期统一计算。运输阶段：所有海带苗均来自荣成内部，养殖区与育苗场之间距离约为 2 km。养成期的养殖器材每年的投入量按照 10 年的平均使用年限计算。养成期海带生物质碳根据海带干湿比(14.3%~16.7%) (刘涛, 2019; 毛玉泽等, 2018)和含碳率(23.92%±3.21%) (Zhang *et al*, 2012)进行计算。RDOC 根据 DOC 释放量和 DOC 向 RDOC 转化率计算。这方面的研究数据不多。从已有的研究来看，

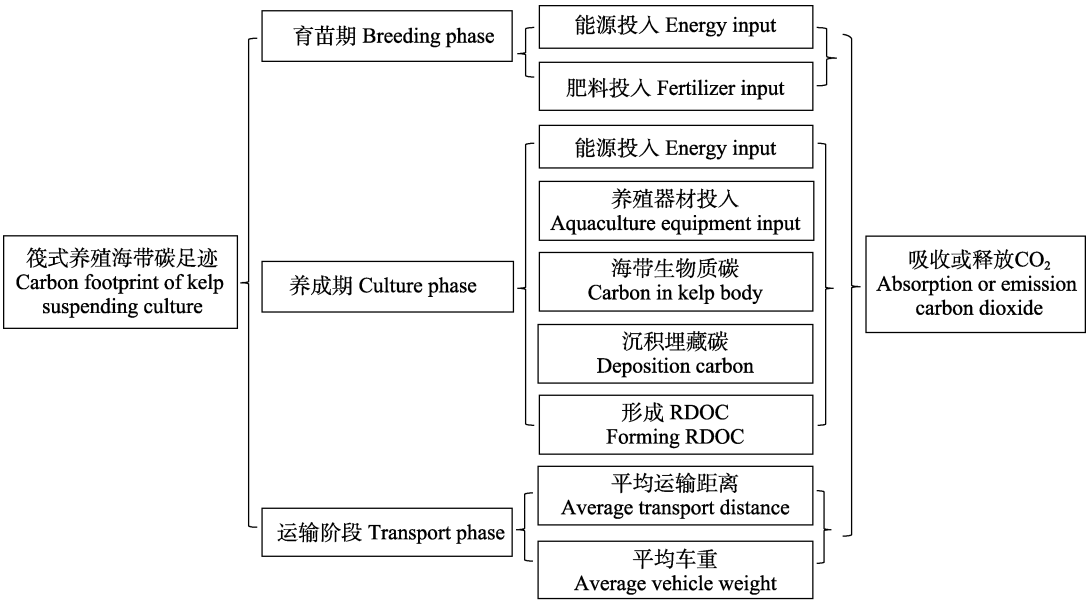

图 2 筏式养殖海带清单分析内容

Fig.2 Inventory analysis of kelp suspending culture

海带的 DOC 的释放量范围为 470.1~1030 mg C/(m^2·d) (Gao *et al*, 2021; Weigel *et al*, 2021; 尼志杰等, 2022)，大型藻类生长过程中释放的 DOC 转化为 RDOC 的比例在 33%~78%范围内(Gao *et al*, 2021; Watanabe *et al*, 2020; Zhang *et al*, 2017; Krause-Jensen *et al*, 2016)。本研究计算的是桑沟湾养殖海带碳足迹，故采用 Gao 等(2021)对桑沟湾海带的研究结果进行计算，即海带生长过程中 DOC 释放率为 470.1 mg C/(m^2·d)，DOC 向 RDOC 的转化率为 37.8%。沉积埋藏碳根据单位面积沉积碳年增量[83 g C/(m^2·a)] (刘赛等, 2018)和单位产量(1 t)对应面积(78.8 m^2)计算。

1.2.3 *计算方法* 本研究依据生命周期评价法的要求，对山东省的养殖海带“从摇篮到大门”的碳足迹进行测算。计算公式为：

$$CF=\sum_{i=1}^{n}V_i\times F_i$$

式中，CF 为养殖海带碳足迹(kgCO_2e)，V_i 表示第 i 种资源或能源的消耗/产出量；F_i 表示第 i 种资源或能源的排放因子。

2 计算结果

生产 1 t 海带的相关数据、数据来源和计算结果见表1。由表1可知，养殖海带的碳足迹为–95.93 kgCO_2e/t，其中，海带的 CO_2 吸收量为 170.23 kgCO_2e/t，排放量为 74.30 kgCO_2e/t (育苗期占 2.24%，养成期占 97.76%，运输阶段仅占 0.000 05%)。

海带养殖各生产环节碳排放情况见图 3。由图 3 可知，育苗期和苗种运输是碳排放环节，分别为 1.66 kgCO_2e/t 和 4.00×10^{-5} kgCO_2e/t；海带养成期是碳汇环节，为–97.59 kgCO_2e/t。

育苗期 CO_2 排放情况见图 4，育苗期碳排放源有 4 项，电能产生的碳排放为 0.85 kgCO_2e/t，占育苗期碳排放量的 51.13%，为整个生命周期排放量的 1.14%。育苗过程中柴油的碳排放量为 0.81 kgCO_2e/t，占育苗期碳排放量的 48.73%，为整个生命周期排放量的 1.09%；2 种肥料使用过程排放量分别为 2.00×10^{-3} 和 3.00×10^{-4} kgCO_2e/t，占育苗期碳排放量的 0.14%。

海带养成期为 CO_2 的汇(表 1)。每养殖 1 t 海带能固定 170.23 kgCO_2，包括海带生物质碳固定 136 kgCO_2，占比约为 79.9%，沉积埋藏碳固定 23.98 kgCO_2，占比约为 14.1%，RDOC 固定 10.25 kgCO_2，占比约为 6.0%。养成期的养殖器材(包括聚乙烯材质的浮绠、橛绳等)产生的 CO_2 排放量占养成期排放量的 95.95%，为整个生命周期排放量的 93.81%；养殖期间用船所消耗的柴油，其 CO_2 排放量占养成期的 4.05%。

3 分析与讨论

养殖海带的碳足迹评估结果显示，养殖期的养殖设施器材是主要的 CO_2 的源，是减排的关键控制点。聚乙烯材料具有抗腐蚀、拉力大等特点，是养殖海带所用的浮绠、橛绳等的主要材料，目前尚未有合适的低碳替代品。养殖器材计入碳足迹的 CO_2 释放量是依据其使用年限来计算的，本研究按照通常的使用年限

表 1　生产 1 t 海带的相关数据及碳足迹计算结果

Tab.1　Relevant data and carbon footprint calculation results for production of 1 t kelp

养殖生命过程 Life cycle stage	项目 Items	数据 Data	碳排放系数/($kgCO_2e/kg$) Carbon emission factor	CO_2 排放量 CO_2 emissions/kg
育苗期 Breeding phase	柴油 Diesel	0.375 kg①	2.17③	0.81
	电能 Electric energy	0.86 度①	0.997③	0.85
	硝酸钠 $NaNO_3$	1.1 g①	1.63④	2.00×10^{-3}
	磷酸二氢钾 KH_2PO_4	0.16 g①	1.53④	3.00×10^{-4}
运输阶段 Transport phase	运输距离 Transportation distance	2 km①	0.172④	4.00×10^{-5}
	车重 Vehicle	6 t①		
	运输量 Transportation volume	3500 万株		
养成期 Culture phase	聚乙烯材料 Polyethylene	115.8 kg②	0.602 9⑤	69.70
	柴油 Diesel	1.34 kg①	2.17③	2.94
	海带生物质碳 Kelp biomass carbon	37.1 kg	–44/12⑥	–136.00
	沉积埋藏碳 Deposition carbon	6.54 kg	–44/12⑥	–23.98
	惰性有机碳 RDOC	2.79 kg	–44/12⑥	–10.25
	碳足迹 Carbon footprint			–95.93

注：①数据来自荣成市寻山集团；②数据来自刘涛(2019)；③柴油和电的碳排放系数来自 IPCC 排放因子数据库；④公路运输、KH_2PO_4 和 $NaNO_3$ 的碳排放系数来自 CLCD 0.7 数据库；⑤数据来自李蔓(2008)；⑥44/12 为 CO_2 与碳的相对分子质量比。电能的碳排放系数单位为 $kgCO_2e/kW·h$，公路运输的碳排放系数单位为 $kgCO_2e/(t·km)$。

Note: ① Data from Rongcheng Xunshan Group; ② Data from Liu (2019); ③ Carbon emission coefficients of diesel and electricity are from IPCC emission factor database; ④ Carbon emission coefficients of road transportation, KH_2PO_4 and $NaNO_3$ are from CLCD 0.7 database; ⑤ Data from Li (2008); ⑥ 44/12 is the relative molecular mass ratio of carbon dioxide to carbon. The unit of carbon emission coefficient of electric energy is $kgCO_2e/kW·h$, and the unit of carbon emission coefficient of highway transportation is $kgCO_2e/(t·km)$.

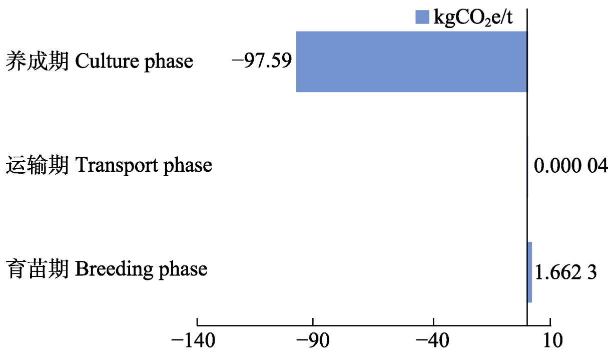

图 3　养殖海带各个生产环节的 CO_2 排放量

Fig.3　CO_2 emissions of each production phase of kelp mariculture

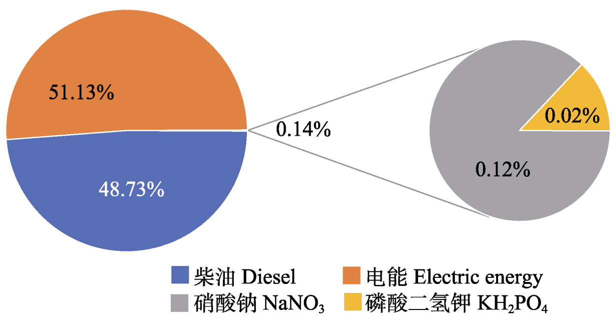

图 4　育苗期各环节 CO_2 排放占比

Fig.4　Proportion of CO_2 emissions during the breeding phase

10 年计量。因此，在积极研发低碳新材料的同时，可通过延长其使用年限的方式降低碳排放。经计算发现，养殖器材的使用年限每延长 1 年可使养殖海带减排 8%左右。建议养殖过程中加强日常维护和保养等管理手段，减少海水对其的损害等，以延长养殖设施器材的使用年限。

柴油、电等能源的消耗贯穿在育苗、苗种运输及养殖整个过程中。研究结果显示，因能源消耗而释放的 CO_2 总计为 4.6 kg，仅占 CO_2 释放总量的 6.19%，但是，本研究所用的海带苗来自荣成当地，并且养殖海域在桑沟湾内，离岸距离近，所以运输过程的 CO_2 释放量不高。海带养殖区域没有足够的育苗场，苗种来自外地，养殖区逐渐从近岸向深远海扩展，都会因能源消耗的增加而增大 CO_2 的排放量，会使得碳足迹增大。因此，调整能源结构，提高能源利用效率，促进海上风能、光伏等清洁能源的使用等措施在海带养殖产业中依然具有重大意义。另外，建议加强产业链

的统筹布局，如基于养殖需苗量来配置育苗场，以减少运输过程的碳排放。

已有的基于生命周期评价法评估投饵型养殖生物的碳足迹(吴飞飞等，2011；付晓洋等，2016；朱林等, 2015; Gephart *et al*, 2021)，结果显示(图 5)，养殖双壳类的碳足迹为 1414 kgCO_2e/t；养殖对虾的碳足迹为 17 405 kgCO_2e/t；团头鲂(*Megalobrama amblycephala*)的碳足迹约为 29 000 kgCO_2e/t；大黄鱼(*Larimichthys crocea*)通过改良养殖模式，可将其碳足迹从 76 000 kgCO_2e/t 降至 10 700 kgCO_2e/t。养殖海带的碳足迹为–95.93 kgCO_2e/t，能够起到养殖负排放的作用。海带之所以能发挥负排放的作用，主要源于其作为初级生产者的碳汇能力。最初的研究主要关注于养殖海带形成的生物质碳(张继红等，2005)。随着研究的深入，证实沉积埋藏碳(Sui *et al*, 2019；聂梦晨等, 2022)和海带生长过程释放 DOC 及碎屑在微生物作用下形成的 RDOC (张永雨等, 2017)都是渔业碳汇的重要部分，也是海洋中长久稳定碳库的重要存在形式。如果不考虑 RDOC 和沉积埋藏部分，会使养殖海带的碳吸收低估近 20%。本研究以桑沟湾的养殖海带为研究对象，得出每养殖 1 t 海带形成的 RDOC 能够固定 10.25 kgCO_2。已有研究结果显示，褐藻生长过程中释放 DOC 的范围为 310~1030 mg C/(m^2·d) (Gao *et al*, 2021; Weigel *et al*, 2021；尼志杰等, 2022; Reed *et al*, 2015)；释放 DOC 向 RDOC 转化比例为 33%~78% (Gao *et al*, 2021; Watanabe *et al*, 2020; Zhang *et al*, 2017; Krause-Jensen *et al*, 2016)。若按照以上结果来计算，养殖 1 t 海带能够形成的 RDOC 可能在 5.90~46.35 kgCO_2 范围。另外，大型藻类碎屑形成的 POC 一部分直接沉降形成沉积埋藏碳，另一部分则会在“微生物碳泵”的作用下形成 DOC，继而形成 RDOC (Jiao *et al*, 2010; Chen *et al*, 2020)。然而，迄今为止未见海带碎屑形成 RDOC 的相关报道，所以，本研究并未将海带碎屑形成的 RDOC 部分计算在内，可能会使测算结果偏低。目前，能查到的相关报道显示，浮游植物(蓝藻)降解产生的 RDOC 约占其干重的 7% (Shi *et al*, 2017)；浒苔(*Ulva prolifera*)生物体降解产生的 RDOC 约占藻类生物质碳的 1.6% (Chen *et al*, 2020)。按照以上的比例计算，海带在养殖过程中形成的碎屑直接降解产生的 RDOC 可能为其总固碳的 4.0%~17.5%。当然，不同海区的养殖条件、养殖品种、养殖模式的差异也会使得不同养殖区之间形成沉积埋藏碳的速率存在差异。鉴于 RDOC 碳汇量的不确定性和不同海区之间形成沉积埋藏碳速率的差异，

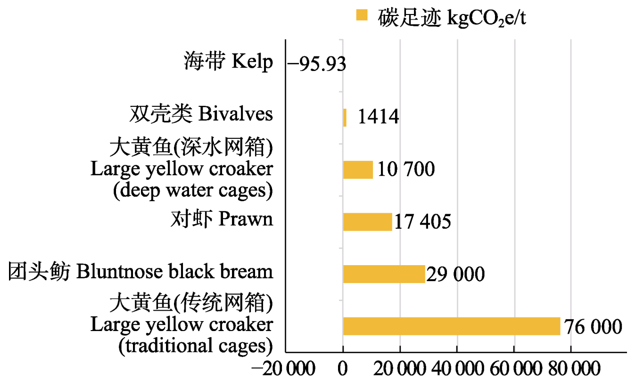

图 5 不同养殖品种碳足迹对比

Fig.5 Comparison of carbon footprints of different breeding species

因此，需要深入研究 RDOC 的形成过程与机制、沉积埋藏碳的沉积速率等问题，以提高碳足迹的计算精度。随着我们对养殖海藻(海带等)碳汇功能认知的深入，大型藻类养殖在海洋负排放中将会发挥更大的作用。

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Carbon Footprint Assessment of Cultured Kelp Based on Life Cycle Assessment

SUN Wei[1], ZHANG Jihong[1,2①], WU Wenguang[1], LIU Yi[1], ZHONG Yi[1], WANG Xinmeng[1], KANG Qinzi[1]

(1. *Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Key Laboratory of Sustainable Development of Marine Fisheries, Ministry of Agriculture and Rural Affairs, Qingdao, Shandong* 266071, *China*; 2. *Laboratory for Marine Fisheries Science and Food Production Processes, Pilot National Laboratory for Marine Science and Technology* (*Qingdao*), *Qingdao, Shandong* 266071, *China*)

Abstract China has the largest population and contributes the most to greenhouse gas emissions in the world. Given the background of low-carbon emissions elsewhere, how to carry out emission reduction activities scientifically and rationally is a question that individuals, enterprises, governments, and countries must seriously consider. The carbon footprint refers to the total amount of greenhouse gases emitted by a commodity or service during the entire life cycle of the product, including production, transportation, use, and disposal. The carbon sink effect of cultured macroalgae in coastal waters is receiving considerable attention. However, international research on macroalgal carbon sinks is still poor, especially the carbon footprint of cultured macroalgae, which makes it impossible to include the carbon sinks of macroalgae within the scope of emission reductions such as "blue carbon." Therefore, by calculating the carbon footprint of macroalgae, the carbon emissions of each stage in the entire life cycle can be determined, and subsequently scientific emission reduction measures can be formulated based on the calculated carbon footprint results of each stage to reduce emissions. Kelp (*Saccharina japonica* Areschoug) is the main macroalgae cultured in China. It has obvious advantages in aquaculture resources and has a very large potential for the development of carbon sinks. As a primary producer in the sea, organic matter is generated through photosynthesis, and carbon sequestration occurs during the kelp growth phase. However, CO_2 is released during seedling growth, electricity utilizing of equipments, fuel consumption on boats, and facilities for culture. To explore the sources and sinks of CO_2 emissions from kelp throughout the entire culture cycle and to establish a standard system for evaluating the carbon footprint of macroalgae production, based on the life cycle assessment theory, a carbon footprint calculation method for raft-cultured kelp was established in this study. The cradle-to-gate carbon footprint of cultured kelp in Sanggou Bay was calculated, and the main influencing factors of the carbon footprint and possible sources of error were analyzed. The life cycle assessment method included four parts: Goal and scope definition, inventory analysis, impact assessment, and interpretation of results. One ton of produced kelp was recorded as the functional unit of the carbon footprint of cultured kelp, and the entire life cycle of cultured kelp to form a kelp product was divided into three phases: Breeding, transport, and culture. The carbon footprints of the three stages were analyzed. The results showed that the carbon footprint of 1 t of kelp farming is –95.93 kgCO_2e, which indicates that the entire process from breeding to growth and harvest is a carbon sink process. Among them, the carbon emission is 74.30 kgCO_2e, and the carbon absorption is 170.23 kgCO_2e. A carbon sink of 79.9% is in the form of kelp biomass carbon, 14.1% exists in the form of deposited buried carbon, and 6.0% exists in the form of refractory dissolved organic carbon (RDOC). Deposited buried carbon and RDOC can accumulate in the deep sea or on the seafloor for a long time. Previous studies on the carbon sink capacity of primary producers have primarily focused on biomass carbon formed by them. Further research confirmed that DOC released during the growth stage of kelp and RDOC formed by detritus under the action of microorganisms and deposited carbon are all important parts of fishery carbon sinks and are also important forms of long-term stable carbon pools in the ocean. If RDOC and deposited carbon are not considered, the carbon sink of cultured

① Corresponding author: ZHANG Jihong, E-mail: zhangjh@ysfri.ac.cn

kelp will be underestimated by approximately 20%. Of course, differences in culture conditions, species, and modes in different seas make the formation rate of deposited carbon different. In addition, the formation process and mechanism of RDOC require further study. Aquaculture facilities were the main carbon source, and their carbon emissions accounted for 93.81%. Our research found that emission reduction can be achieved by extending the service life of aquaculture facilities. Each year of service life extension can reduce the emissions by 8%. The carbon emissions from diesel and electricity accounted for 5.05% and 1.14%, respectively. Sanggou Bay is a typical coastal water; therefore, the demand for energy during the breeding process is low. When the aquaculture area expands to the open sea, the proportion of the energy carbon footprint will greatly increase, and even become the main carbon source. Fertilizer and transportation account for only one ten-thousandth of carbon emissions. The kelp seedlings in the breeding area of Sanggou Bay come from Rongcheng; therefore, the amount of CO_2 released during transportation was not high. Insufficient numbers of nurseries for kelp breeding will result in the seeds coming from other places, and the amount of CO_2 released during transportation will also increase greatly. Therefore, strengthening the overall layout of the industrial chain is of great significance in reducing carbon emissions during transportation. With further understanding of the carbon sink function of cultured seaweeds, macroalgal cultures will play a more important role in ocean emission reduction. This study provides technical support for the establishment of carbon footprint evaluation procedures and standard systems for macroalgal farming.

Key words　Carbon footprint; Kelp; Mariculture; Sanggou Bay; Life cycle assessment