学校编码：10384　　　分类号＿＿＿＿＿＿＿密级＿＿＿＿
学号：B200134002　　　UDC ＿＿＿＿＿＿＿＿＿＿＿＿＿

学 位 论 文

养殖富营养化修复藻类的营养生态学研究

Study on Nutrient Ecology of Seaweeds Used for Remediating Maricultural Eutrophication

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申请学位级别：工学博士

专 业 名 称：环境科学

论文提交日期：2004 年 5 月

论文答辩时间：2004 年 7 月

学位授予单位：厦门大学

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2004 年 05 月

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2004 年 06 月 10 日

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摘　要

海水养殖的重要性不言而喻，其对近海生态环境的负面影响也很严重，尤其是造成海水富营养化及赤潮的频发。大型海藻，特别是江蓠属大型海藻，拥有生长快、能快速吸收营养、有大的氮储存库等特性，是营养污染的良好修复生物。目前在江蓠的营养吸收、品种选择和搭配以及环境响应上还有待于更深入研究。本论文挑选 2 种江蓠属大型经济海藻——菊花心江蓠（*Gracilaria lichevoides*）和龙须菜（*G. lemaneiformis*），考察环境因子、营养盐因子对两种海藻的生长和氮、磷吸收影响，及在适宜条件下龙须菜的氮营养特性，并通过中试试验校正了水运动对海藻氮吸收的影响；在此基础上，考察了不同菊花心江蓠放养密度系统对脉冲营养加富的响应以及不同龙须菜密度在骨条藻赤潮消亡中的作用和系统的响应，同时调查了菊花心江蓠在围隔对虾综合养殖中净化和修复效果；现场研究了菊花心江蓠在养殖池塘、网箱养殖区以及龙须菜在网箱养殖区对营养的净化和 DO 的修复，并对一应用实例进行分析。通过室内、中试及现场三阶段研究，获得主要结果如下：

1. 菊花心江蓠的生长适温 24~36 ℃、盐度 20~35、光强 120~300 $\mu E \cdot m^{-2} \cdot s^{-1}$；龙须菜生长适温 14~24.5 ℃、盐度 20~35、光强 100~240 $\mu E \cdot m^{-2} \cdot s^{-1}$。在此基础上，通过均匀设计探讨三因子交互作用对海藻生长的影响，优选得光强 287.23 $\mu E \cdot m^{-2} \cdot s^{-1}$、温度 31.30 ℃、盐度 32.10 时，菊花心江蓠有最佳的生长率 16.77 %/d。
2. 采用黑白瓶试验法，筛选出 POPSO 适于作为龙须菜培养用 pH 缓冲物质，使用终浓度为 20~25 $mmol \cdot L^{-1}$，该缓冲剂主要是通过稳定介质中的 DIC 浓度从而促进海藻的生长；并计算得出龙须菜生长的 CO_2 限制浓度为 5.25 $\mu mol \cdot L^{-1}$。

3. 修复生物菊花心江蓠和龙须菜对 N、P 吸收速率较大：对 NO_3-N 的最大吸收速率为 57.35、54.26 $\mu mol \cdot gDW^{-1} \cdot h^{-1}$，$NH_4$-N 为 36.30、34.23 $\mu mol \cdot gDW^{-1} \cdot h^{-1}$，$PO_4$-P 为 3.120、2.802 $\mu mol \cdot gDW^{-1} \cdot h^{-1}$。受环境的影响，室外的吸收速率略低于室内，但更符合现场实际情况。

4. 菊花心江蓠和龙须菜对 N、P 的吸收随着温、盐、光、pH 及 N、P 浓度的增加而增加；介质的不同 N/P 比不影响海藻对 N 的吸收速率，但对 P 的吸收速率影响显著；两种海藻都按介质中的存在比例吸收各种化合态 N，在适宜环境因子下，吸收氮、磷量的比值都在 9~11 之间。

5. 龙须菜生长随着介质 N 浓度的升高而增加，不同化合态 N 对生长影响不显著；高 N 能促进藻红素（PE）的生成，通过 PE/Chla 比看，PE 主要作为储存 N 的功能和积累物质。

6. 水运动状况是影响大型海藻营养吸收的主要因素，流速 3 $cm \cdot s^{-1}$ 时，龙须菜 4h 内比静水状态多吸收 24 %的 N 和 31 %的 P。

7. 1.5 $Kg \cdot sm^{-3}$ 放养密度的菊花心江蓠可以有效地抑制环境中微藻水华的发生并保持较低环境营养水平。一定密度的龙须菜（>1 $Kg \cdot sm^{-3}$）可以加速骨条藻赤潮的消亡，促进微藻优势种类数量增加，并能缓冲赤潮崩溃后的生态恶化；并在现场初步探讨了室内与海区同步试验，预报自然海区赤潮消亡时间及最低 DO 出现时间的可行性。

8. 对虾养殖围隔，菊花心江蓠能有效地调控水质，降低营养盐胁迫，抑制水体中弧菌，与单养虾相比，虾藻混养对虾平均体长增加 2.1cm，成活率提高 30%以上。

9. 现场考察了菊花心江蓠和龙须菜对富营养化水体 N、P 的修复和净化及对 DO 的补充，池塘中两者的修复效果非常明显。

关键词：大型海藻；生物修复；养殖富营养化

Study on Nutrient Ecology of Seaweeds Used for Remediating Maricultural Eutrophication

ABSTRACT

The negative effects of mariculture on coastal marine environments has been increasing, and offer result in eutrophication of seawater and frequent break-out of HAB, even if its importance is self-evident. Seaweed, especially *Gracilaria* spp. is regarded as a suitable remedial plant, which holds many advantageous characters such as rapid growth, higher nutrient uptake rate and larger nitrogen storage pools than other bio-remedies. At present, further researches on seaweed selection, nutrient uptake and response to environment are imperative. Two species of economic seaweeds ---- *G. lichevoides* and *G. lemaneiformis*-- were selected as experimental seaweeds in this study. Experimental contents included the influence on nitrogen (N) and phosphorus (P) absorption made by environment factors, nutrient factors and their cooperation. In metaphase test, further plans based on these experiments mentioned above were carried out, which included response of pulsant nutrient-enrichment to *G. lichevoides* cultured ecosystem with different stocking densities, response of *Skeletonema costatum*'s depression of *G. lemaneiformis* with different stocking densities, and response of related ecosystems. At the same time, purification and remediation functions of *G. lichevoides* in shrimp cultured enclosures were investigated. In field, N and P uptake and dissolved oxygen (DO) compensation in shrimp ponds, in cage culture areas were observed. These models were discussed from a practical angle. With analyzing the data collected in lab，

metaphase test and field, the following conclusions can be drawn:

1. Optimal temperature, salinity and light intensity of the *G. lichevoides* and *G. lemaneiformis* are respectively 24~36, 14~24.5℃; 20~35, 20~35; 120~300, 100~240 $\mu E \cdot m^{-2} \cdot s^{-1}$. With uniform design method, cooperation of the three factors on algal growth has been investigated and optimum result has been achieved, which is 287.23$\mu E \cdot m^{-2} \cdot s^{-1}$, 31.30℃, 32.10, and the algal optimal growth rate is 16.77%/d.
2. By light-dark bottles, POPSO----a zwitterionic organic matter---- has been selected which is suitable to culture *G. lemaneiformis* as a pH buffer, final usage concentration is 20~25 $mmol \cdot L^{-1}$. Effect of the buffer on the algal growth is based on keeping dissolved inorganic carbon (DIC) steady within culturing medium, and supplies the plant with more C sources than blank treatments. In this experiment, limiting growth concentration of carbon dioxide (CO_2) to *G. lemaneiformis* has been reckoned and the value is 5.25$\mu mol \cdot L^{-1}$.
3. N and P uptake rates of *G. lichevoides* and *G. lemaneiformis* are high, the highest uptake rate of nitrate is 57.35, 54.26$\mu mol \bullet gDW^{-1} \bullet h^{-1}$; of ammonium is 36.30, 34.23$\mu mol \bullet gDW^{-1} \bullet h^{-1}$; of phosphate is 3.120, 2.802$\mu mol \bullet gDW^{-1} \bullet h^{-1}$. Influenced by environment, the uptake rates in outdoors are a little lower than in lab. But the kinetics parameters (V_{max} and K_s) got by both in outdoors and in lab are similar. This result is more congruent to factual conditions in fields.
4. N and P uptake rates of *G. lichevoides* and *G. lemaneiformis* are incremental with the environmental factors, such as temperature, salinity, light intensity,

pH, N and P concentrations increased; the N/P ratio in medium doesn't influence N uptake rate, but evidently influences P uptake rate of both seaweeds; According to the subsistent ratios in medium, both algae uptake three chemical combination form nitrogen (nitrate, nitrite, ammonium), under the optimal conditions, the N/P ratios of both uptake quantities are between 9 and 11.

5. Growth rate of *G. lemaneiformis* is increased after N adding in medium, different chemical combination form nitrogen has not evident influence upon the algal growth; High N concentration can promote accumulation of R-phycoerythrin; From the ratio R-phycoerythrin to Chlorophyll-a of *G. lemaneiformis*, the main function of R-phycoerythrin is nitrogen accumulation and deposit materials, when N is short in medium, catabolism of R-phycoerythrin as a N source is intensified for growth of the algae.
6. Water movement is important for algal growth and nutrient uptake as it changes the algal surrounding water, thereby replenishing its nutrient supply, removing waste products, etc. At the movement rate of $3 cm\cdot s^{-1}$, N and P uptake of *G. lemaneiformis* are more than the still water, exceeds 24% N and 31% P.
7. The stocking density of $1.5\ Kg\cdot m^{-3}$ *G. lichevoides* can effectively restrain outbreak of phytoplankton bloom and keep low level of nutrient in medium. Above $1.5\ Kg\cdot m^{-3}$ stocking density of *G. lemaneiformis* can accelerate subsidence of the *Skeletonema costatum*'s bloom, promote increasingly dominant species numbers of microalgae, and alleviate deterioration of water quality after crashes of HAB. Furthermore, in field and in lab, synchronous experiments were carried through, and primary discussed the

feasibility for forecasting the timing of HAB crashes and emergent schedule the lowest concentration of DO.

8. Within shrimp culture enclosures, *G. lichevoides* can effectively regulate and control water quality, lower concentration of nutrients, restrain the Vibrio abundance. Comparing with mono-culture shrimp treatment, average body length of stocking shrimp augments 2.1cm and survival rate elevates above 30% in shrimp-algae poly-culture treatments.
9. In shrimp ponds and cage-culture areas, N and P uptake and DO compensation of *G. lichevoides* and *G. lemaneiformis* were probed into. Both are evident in shrimp ponds, but in cage culture areas, the DO compensation is very evident, and N and P uptake is not as evident as DO, because the water body in bay is running. In demonstration site----Wujiao Bay, utilizing *G. lemaneiformis* remediated and purified waste water from abalone culturing farm, the results are good.

Key words: Seaweed; Phytoremediation; Maricultural eutrophication.

第一章　前言

沿岸海域是全球单位面积生物生产力最高的区域之一，是人类可利用生物资源的重要生产基地；沿岸带也是人类生活、经济活动最为频繁的区域，是社会与经济的重要组成部分；又是陆、海、气各种理化过程以及人类干扰作用的强度承受区域，是环境变化的敏感区和生态系统的脆弱带。

在全球范围海洋捕捞产量徘徊不前的前提下（图 1），海产品的增长在更大程度上要依靠迅速发展的水产养殖业，主要是沿岸的海水养殖业。据 FAO 统计，在 1986 年至 1996 年间，全球的海水养殖以每年 10%的速度增长，10 年间产量增加了一倍多[1]；目前人类消费的渔产品中 1/4 以上是养殖生产的[1]。海水养殖业已成为世界的一个新的经济增长点，如 1997 年世界鲑鱼养殖产量为 644,000 t，价值超过 20 亿美元，主要由海水网箱养殖生产[2]。

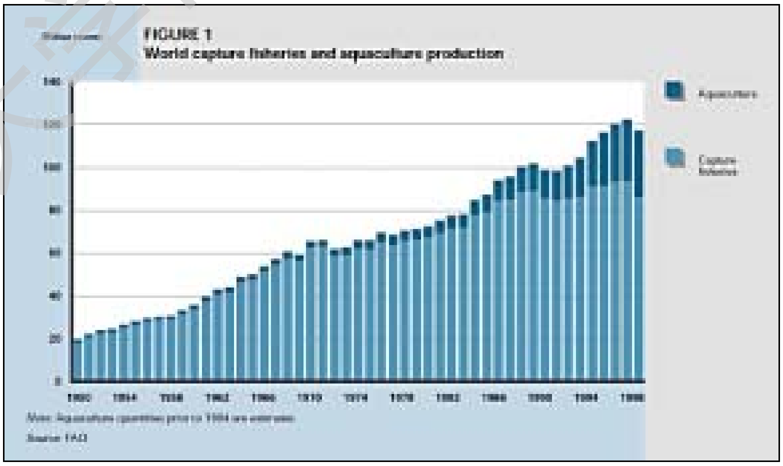

图 1　历年世界范围渔产品捕获量和养殖产量对比（FAO,2002）

Figure 1 Compared fished yields with cultured yields in the world (FAO,2002)

海水养殖业也是我国渔业的重要组成部分，在国民经济是占有特殊的地位，为人们提供丰富的动物食品和工业原料。自上世纪 80 年代以来，我国的海水养殖业已开发的养殖面积 40 多万 hm^2，海水养殖从业人员逾 300 万人。养殖产量 1982 年为 86 万 t，1997 年为 792 万 t，增长了近 10 倍，2002 年已达到 1213 万 t，从占海洋渔业产量的不足 10%上升到 46%（图 2），并连续多年居世界首位[3]。海洋渔业产业在海洋各产业也占了非常重要的地位，2003 年海洋渔业总产值达 2821.66 亿元，占全国海洋产业总产值的 28.0%，居各产业第一位[3]。

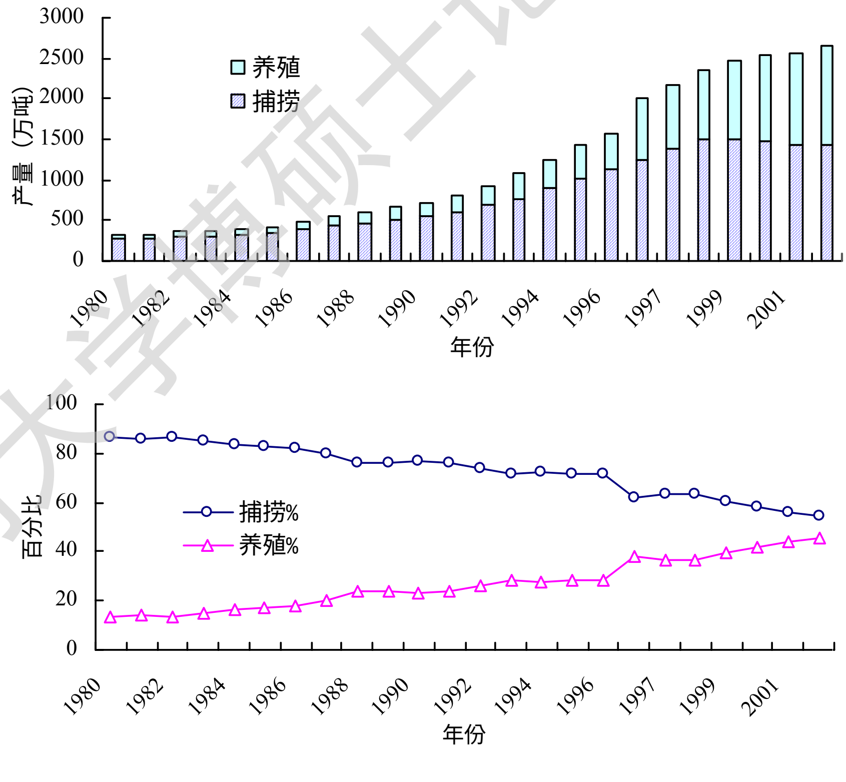

图 2　历年全国捕捞和养殖产量分析

Figure 2 Variations of fished and cultured yields from 1980 to 2001

第一节 海水养殖对环境的影响

尽管我国海水养殖业有了长足的发展，但也应看到其存在着严重的问题，尤其是在自身污染和生态破坏方面：

掠夺性使用养殖资源，没有考虑长远的生态效益和环境效益，致使养殖量严重超过其环境容纳量，养殖技术的落后和养殖对象搭配的不合理，已造成了严重的生态学问题：养殖海区生物多样性下降、养殖生物种质退化等；养殖自身的污染也已达到了相当严重的地步，在局部养殖区，有机污染和生物污染（包括病毒、细菌和寄生虫等）造成养殖生物的营养胁迫和疾病的流行。

下面分两部分论述海水养殖对环境造成的影响：

1 海水网箱养殖对环境的影响

我国的海水网箱养殖始于 20 世纪 80 年代初，近几年，由于育苗技术的突破，海水网箱养殖发展迅速。据中国渔业统计年鉴[3]：1999 年，全国海水鱼类养殖产量为 33.88×10^4t，是 1989 年的近 10 倍；其中海水养殖网箱数量由 1994 年的 16 万只，增至 2000 年的 70 多万只，养殖种类近 40 种，年产量超过 44×10^4t。

网箱养殖在对人类提供蛋白质的同时，也破坏了沿岸和海洋资源和环境[4]。本文综述了近 20 年来国内外关于海水网箱养鱼对环境影响的研究概况，包括网箱养鱼对养殖海区水体的污染、对沉积物的影响、逃逸鱼的影响及可能造成的基因污染、养殖过程中使用化学药品污染以及养殖活动导致海区生物多