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博 士 学 位 论 文

全日潮海区红树林造林关键技术的生理生态基础研究

Studies on the Eco-physiological Mechanisms for the Key Techniques in Mangrove Afforestation in the Diurnal Tidal Region

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摘　要

本研究针对制约当前我国红树林造林的最关键的两个自然因素：潮汐淹水和污损动物胁迫进行系统研究，目的是为科学划分红树林宜林地提供关键的技术参数，为红树林污损动物防治提供技术方法，从而提高红树林生态恢复工程的成功率。研究内容包括：1. 红树植物淹水胁迫研究。在全日潮海区滩涂上建造野外试验平台，围绕当地平均海平面设置了 8 个滩面高程梯度，开展白骨壤(*Avicennia marina*)、桐花树(*Aegiceras corniculatum*)、秋茄(*Kandelia obovata*)、红海榄(*Rhizophora stylosa*)和木榄(*Bruguiera gymnorrhiza*)等 5 种红树植物幼苗淹水胁迫试验，探索这 5 种红树植物在北部湾海区滩涂造林的宜林临界线。平台使幼苗除滩面高程有梯度差别外，其他如光照、海水盐度、基质性质和营养等立地条件达到最大程度的一致。2. 红树林污损动物生态学研究。采用试验圆柱模拟红树，探索广西英罗湾红树林污损动物的初始附着规律和数量变化动态，结合白骨壤呼吸根上和桐花树茎上的污损动物群落，总结广西红树林污损动物群落演替规律。3. 红树林污损动物防治研究。根据广西英罗湾红树林污损动物生态规律，使用 2 种农药各设置 4 个浓度和 4 个防治频度，采用喷雾方式，对比研究不同防治措施对红海榄幼苗及污损动物的生理生态影响。并初步探索了红树林污损动物的生物防治途径。结果如下：

1. 五种红树植物幼苗对淹水胁迫的反应各不相同，采用不同的生长策略应对胁迫生境。桐花树幼苗的茎在低滩面高程生境加快延长，而叶在中等高程生境中生长较好；生物量分配的变化不大，趋向于叶累积较多。白骨壤幼苗的茎延长受到了低滩面高程处理的促进，但叶似乎对淹水胁迫不敏感，生物量较多地分配在茎上。中等高程生境中秋茄幼苗的生长高度较高，节数、叶数和大根数越多，叶面积和叶保存率越大；在任一高程，秋茄幼苗各新生器官生物量分配均表现为：茎>根>叶，各新生器官及全株生物量的最大值出现在中等高程。木榄和红海榄的存活和生长特征较相似，对梯度淹水程度反应强烈：在较高生境，这两个种的幼苗存活率较高，茎延长较快，叶面积和叶保存率高，生物量累积也较多，并趋向累积于叶。

2. 对于不同的淹水胁迫程度，五种红树植物的生理指标反应变化各异。在-40 和-30 cm 低滩面高程处理组，白骨壤幼苗叶绿素含量较高。在-10 至 30 cm 处理组，白骨壤幼苗叶绿素 a 和总叶绿素含量随滩面高程增大而降低；而各高程组的叶绿素 b 含

量差异不大。白骨壤幼苗根系和叶片中 SOD、POD 和 CAT 对淹水胁迫的反应较为一致，即中等滩面高程生境下酶活性较高。

桐花树幼苗叶片的叶绿素 a、b 和总含量均随滩面高程升高而降低，Chl (a/b)随滩面高程升高而增大。较低滩面高程处理组（-40 到 0 cm）幼苗叶片中 SOD 活性远大于较高滩面高程处理组 (-10 至 30 cm)。不同处理组间根系中 SOD 活性变化不显著，梯度效应很弱。中等滩面高程生境下根系中 POD 活性较高；较小高程下叶片中 POD 活性较高。桐花树幼苗根系和叶片中 CAT 活性规律较一致：较小高程生境下 CAT 活性较高。

低滩面高程生境下秋茄幼苗叶片叶绿素含量显著地高。Chl (a/b)则随滩面高程上升而增大。根系中 SOD 和 POD 的分布规律较为一致，都以 0cm 处理组的活性最高。叶片中 SOD 和 POD 活性的变化则相反，叶片 SOD 随高程增大而降低，POD 则随高程增大而增大。根系中 SOD 和 POD 活性的水平与幼苗全株生物量的关系均呈显著相关，叶片中的则无此相关性。

小高程组红海榄幼苗叶片叶绿素 a 显著受损，叶绿素 b 则相对较轻；叶绿素 a/b 比值随滩涂高程降低而变小。长时间淹水诱导根系中 SOD 活性上升，叶片中则表现为中等高程组酶活性较低。叶片和根系中 POD 活性均随高程降低而加大。

小高程生境对木榄叶片叶绿素含量的促进作用较微弱，总体上大高程生境有更利于叶绿素含量上升；但较长时间的淹水胁迫使叶绿素 a/b 比值反而较高。小高程处理均促使叶片和根系中 SOD 和 POD 活性增强。同一高程组的木榄幼苗根系中 SOD 和 POD 活性均高于叶片的数倍。

3. 五种红树植物幼苗在不同程度的淹水胁迫下存活率和生长指标表明，它们在全日潮海区抗淹水能力排序为：白骨壤>桐花树>秋茄>红海榄>木榄，这与它们的向海分布序列相符。相对于当地平均海平面，在全日潮海区可以保证比较高的造林成功率的宜林滩面高程分别建议为：白骨壤为-29cm，桐花树、秋茄和红海榄均为+1cm，木榄为+21cm。

4. 在广西红树上共记录到污损动物 29 种。污损动物在茎上的附着高度 h 随树龄和树高 H 增大而增大，但 h/H 比值在达到 91.9%（5a）后随树龄的增加而降低。广西红树林污损动物主要种的耐受干旱能力表现为：白条地藤壶(*Euraphia withersi*)>潮间藤壶(*Balanus littoralis*)>团聚牡蛎(*Ostrea glomerata*)>黑荞麦蛤(*Xenostrobus atratus*)。红树林污损动物的初始附着呈双峰型，分别在 4 月和 10 月；同时污损动物的初始附着量

很大，每个月均超过了 1600 Ind.m^{-2}。红树林污损动物群落结构从单优群落向复杂群落发展，潮间藤壶是构建群落的先锋种，逐渐过渡到白条地藤壶占优势，多年演变成为黑荞麦蛤+潮间藤壶+白条地藤壶群落。模拟试验和群落调查分析结果为红树林污损动物的防治策略提供了重要的基础数据。

5. 防治目标针对污损动物的幼体，采用高频度喷雾防治是本文防污的重要策略。不同的浓度和频度的防治措施，在污损动物附着量、幼苗存活率和生长指标出现了显著的差异。较高的浓度和频度防治取得较理想的防治效果，马拉硫磷防治效果比乐果更好。考虑到农药污染残留问题、经济成本和操作性，采用频度 14d 和浓度 1/800 马拉硫磷（45%乳油）防治红树林污损动物较为适合。生物防治初步研究表明锯缘青蟹(*Scylla serrata*)对较低位置的污损动物清除效果十分明显，致使污损动物的密度、生物量和生物多样性显著下降；但同时锯缘青蟹不能取食较高位置的污损动物，表明多种动物协同防污应是今后红树林污损动物的生物防治的重要技术路线。本文探讨了生物防治的潜在应用生物种类、方式和可行性，并提出了“生态养殖-造林综合体系”的建议。

关键词：红树林；淹水胁迫；宜林临界高程；污损动物胁迫；污损动物防治

Studies on the Eco-physiological Mechanisms for the Key Techniques in Mangrove Afforestation in the Diurnal Tidal Region

Abstract

Focused on the two key factors determining the chance of successful mangrove afforestation, i.e. flooding and fouling stress, the present study aimed at providing the supporting parameters for reasonable selection of suitable tidal flat for mangrove afforestation, and for controlling technique to the mangrove fouling fauna as well. This study consisted of three aspects, 1) the eco-physiological responses of mangrove plants to flooding stress, 2) the ecology of mangrove fouling fauna, and 3) the controlling of mangrove fouling fauna.

In the flooding experiment, three replicate experimental platforms were constructed on the bare flat in Yingluo Bay in the Beibu Gulf, where a diurnal tide prevailed; and eight different tidal flat elevation (abbreviated as TFE) treatments were created on each platform for the seedling cultivation. The experimental platforms presented the utmost similarities in such habitat conditions like light, salinity, sediment and nutrient, except the gradient degrees of flooding stress. The flooding tolerance of five important mangrove species in China, i.e. *Aegiceras corniculatum* (*Ac*), *Avicennia marina* (*Am*), *Kandelia obovata* (*Ko*), *Bruguiera gymnorrhiza* (*Bg*) and *Rhizophora stylosa* (*Rs*) was examined.

In the ecological study on the mangrove fouling fauna, the cylindrical experimental poles were applied for the first time to simulate the stem of mangrove plant, and to investigate the temporal dynamic rules of mangrove fouling community. The perennial fouling communities on the pneumatophores of *Am* tress and on the stems of *Ac* trees were also sampled for the community succession analysis.

In the antifouling experiment, two kinds of pesticides (malathion and dimethoate) were applied, and four concentrations (1/200, 1/400, 1/600 and 1/800 seawater solution of the original pesticide concentration respectively) and four spraying frequencies (every 3d, 7d, 14d and 28d respectively) were designated to the treatment groups. The growth and physiological responses of *Rs* seedlings under different treatments were measured, so were the fouling fauna communities on the seedlings. Furthermore, a preliminary bio-controlling experiment was conducted.

The results were showed as following.

1. The growth responses to gradients of flooding differed among these five mangrove species, different strategies were adopted to adapt the flooding stress habitats. In *Ac*, stem elongation was promoted at lower TFEs; leaves grew better in moderate habitats; and biomass proportions changed narrowly, with more accumulated in the leaf. *Am* seedling's stem elongation was also promoted by lower TFEs, while its leaf seemed to be insensitive to flooding stress, and more biomass was accumulated in the stem. For the *Ko* seedling, better growth was achieved at the moderate TFEs, with more knots, higher numbers of leaves and cable roots, larger leaf areas, higher leaf conservation rates, and larger biomass accumulation. *Bg* and *Rs* exhibited similar trends in survival and growth, with intense gradients of responses to flooding. Seedlings of both species had a higher survival rate, quicker stem elongation, larger foliar area and conservation, and more biomass accumulation at higher TFEs.

2. The responses in physiological parameters to gradients of flooding varied among these five mangrove species. The chlorophyll contents in leaves of *Am* seedlings were higher in -40cm and -30 cm treatments. Among the TFE of -10 cm to 30 cm, there presented an increase of Chl a and total Chl with the decreasing TFE; while the Chl b changed little. The activities of SOD, POD and CAT responded similarly to the flooding stress, of which higher activity occurred under moderate TFE.

The contents of Chl a, Chl b and total Chl of *Ac* seedlings all increased, while Chl (a/b) decreased with the decreasing TFE. SOD activities in leaves were higher in lower TFE treatments (-40 cm to 0 cm) than those in higher TFE treatments (-10 cm to 30 cm). SOD activities in root changed little among different TFE treatments. POD activities in root were higher under moderate TFE treatments, while high POD activities in leaf occurred under lower TFE. Both the CAT activities in leaf and in root

were higher under lower TFE than those under higher TFE.

The chlorophyll contents of *Ko* seedlings under lower TFE treatments were higher than the higher ones, indicating that the longer waterlogging had a positive promotion to the increase of chlorophyll contents. Both SOD and POD activities in root were higher than those in leaf in the same treatment. In root, the SOD followed the same rule as POD, and both of their maximum occurred in the 0cm YSD. In leaf, there showed an opposite trend, with the TFE increased, the SOD activity decreased while the POD increased. There existed significant correlation between the total biomasses of the seedling and the activities of SOD and POD in root, but none in leaf.

To *Rs* seedlings, larger damage to Chl a occurred in the lower TFE treatments, while relatively less to Chl b. Ratios of Chl (a/b) decreased as the TFE lowered. Prolonged inundation treatments induced higher SOD activities in root, while moderate TFE habitats inhibited the activities in leaf. As the TFE decreased, POD activities in both root and leaf all went up.

A slight promotion to the chlorophyll contents of *Bg* seedlings could be found under lower TFE habitats, however stronger promotion occurred under the higher ones. And the ratios of Chl (a/b) under lower TFEs were higher than those under higher TFEs. Higher SOD and POD activities in both the leaves and the roots were significantly promoted by the lower TFEs. At the same TFE the activities of both SOD and POD in the roots are several times higher than those in the leaves.

3. Comparison of flooding tolerance was mainly based on the survival and growth parameters of seedlings. Flooding tolerance for these species studied decreased in the following order: *Am* > *Ac* > *Ko* > *Rs* > *Bg*, which matched their natural distribution in the intertidal zone. In order to afforest mangrove successfully in the diurnal tidal region, the critical tidal elevation we proposed for *Am* was located at 29 cm under local mean sea level (MSL), while those for *Ac*, *Ko* and *Rs* were at 1 cm above the local MSL, and that for *Bg* was 21 cm above local MSL.

4. Twenty nine species of fouling fauna were recorded on the mangrove trees of Guangxi. The fouled heights (h) went up with the tree ages and the tree height (H), while the ratio h/H reached the maximum (91.9%) at 5a and then decreased with the

tree ages. The drought-tolerance of the major species of mangrove fouling fauna in Guangxi decreased in the following order: *Euraphia withersi* > *Balanus littoralis* > *Ostrea glomerata* > *Xenostrobus atratus*. The larval supply of mangrove fouling fauna in Guangxi presented a two-tip type through the whole year, with one tip on April and another on October respectively. However, we should pay more attention to the fact that the monthly larval supply except January and February exceeded 1600 Ind.m^{-2}. The perennial mangrove fouling community changed from the mono-dominant type to the multi-dominant type, during which *Balanus littoralis* acted as the pioneer species in the earlier stage; and then *Euraphia withersi* dominated the community in the meddle stage; after that the multi-dominant-species *Xenostrobus atratus* + *Balanus littoralis* + *Euraphia withersi* community came into being in the later stage. Results from the simulation experiment and the field investigation played important roles in designing the controlling strategy to mangrove fouling fauna.

5. High frequency of spraying pesticide on the young larval in the early stage was the important strategy applied in our antifouling experiment. The results showed that there existed significant differences in fouling quantities, seedling survivor and growth under different pesticide concentration and spraying frequency, while better result was achieved under denser pesticide and more frequent controlling treatment. Malathion was more efficient than dimethoate. As less pesticide persistence, lower cost and simplified operation were considered, a fouling controlling proposal with spraying frequency of every 14d and Malathion concentration of 1/800 was given. In the biotic controlling experiment, the *Scylla serrata* exhibited efficient clearance capability of the fouling fauna on the lower position while poor on the higher position, pointing out that the multi-species strategy should be applied for the bio-controlling of mangrove fouling fauna in the future. The potential species, methods and feasibility for the further bio-controlling to mangrove fouling fauna were analyzed; and an “ecofarming- afforestation integrated system” was proposed.

Key words: mangrove; flooding stress; critical tidal elevation for mangrove afforestation; fouling fauna stress; antifouling

第一章 前言

1.1 红树林重要生态价值

红树林湿地作为一种特殊的滨海生态交错带，立足于狭长的海岸潮间带滩涂，潮汐循环往复地改变着基质状况，植物群落异质地向水平和垂直延伸，构建起景观上与其它生态系统迥异的三维复合体。这种生物海岸地貌特征极其鲜明，构造复杂多样，开放性、包容性极强，相似性和特异性并存，汇集承载了生境需求、饵料选择、形体大小、营养级别、功能角色上千差万别的各种海洋和陆地生物类群，同时并行着海岸护卫前沿、有机物质“生产车间”、碎屑食物链源端、饵料场、繁殖地、越冬场所、栖息地、幼苗库、“中途加油站”、“避难所”等许多性质各异而又共存的结构和功能载体。我国红树林湿地具有较高的经济和生态价值。据估算广西红树林湿地在木材、果实、近海渔业、减少风暴潮损失、维护海堤、保护耕地、防止侵蚀、保持肥力及生产绿肥、产生氧气、净化空气水体、维持林区动物等方面的经济效益为59 459元· $ha^{-1}\cdot a^{-1}$ [1]。

红树林具有“三高”特性：高生产率、高归还率和高分解率，叶片枝干花果等凋落物构成滨海湿地食物网的深厚基础，表征中国红树林区域性特征的海莲(*Bruguiera sexangula*)、红海榄(*Rhizophora stylosa*)和秋茄(*Kandelia obovata*)的初级生产力分别为29.49、15.37和23.46 $t\cdot ha^{-1}\cdot a^{-1}$，归还率为12.55、6.31和9.21 $t\cdot ha^{-1}\cdot a^{-1}$，半分解期为20-45 d，9-13d，18-56d [2]。近年来大规模种植的无瓣海桑(*Sonneratia apelata*)生产力也较高，深圳的6a无瓣海桑林净生产力达16.92 $t\cdot ha^{-1}\cdot a^{-1}$ [3]。范航清等[4]估算广西山口保护区红树林的地上部总生产力4.58 $t\cdot ha^{-1}\cdot a^{-1}$，理论上每年足以支撑的植食性海洋动物1.22 t鲜重。初级生产力向各营养级消费者转化的过程逐级锐减，高生产力增加了红树林湿地食物链得以延长和途径更多样化的可能性，从而使位于不同营养层次的生物类群丰富多彩。

在总面积约为300万km^2的中国海洋国土，记载了海洋生物物种为20278种[5]。中国红树林湿地以239 km^2的狭长地带，繁衍生息着至少2854种生物，包括真菌136种、放线菌13种、细菌7种、小型藻类441种、大型藻类55种、维管束植物37种、浮游动物109种、底栖动物873种、游泳动物258种、昆虫434种、蜘蛛31种、两栖类13种、爬行类39种、鸟类421种和兽类28种。这些动物中有8种国家一级保护动物，75种二级保护动物。红树林湿地单位面积的物种丰度是海洋平均水平的1766倍[6]。红树林以有限的群体，承担起

我国东南沿海的近海海洋生态安全和可持续发展的重任。1992年至今，海南东寨港、香港米埔、台湾淡水河口、广西山口、广西北仑河口和广东湛江等6块红树林湿地先后被纳入国际重要湿地之列，彰显了中国红树林湿地在全世界濒危生物保存和发展的重要地位。

1.2 中国红树林分布

我国红树林自然分布区南起海南省三亚市(18°13′N)，北到福建省福鼎市(27°20′ N)，并人工引种至浙江省乐清县(28°25′N)。我国红树林生长区域跨越了纬度 10°12′。据推测，我国的红树林在历史上面积可能达 25 万公顷，二十世纪 50 年代尚存 4 万多公顷[7]；最近 50 年间我国红树林面积大幅度减少，2001 年全国红树林资源调查表明现存面积为 22639 ha[8]。

按省级行政区划分，中国现有红树林主要分布在广东、广西和海南，面积分别为 9084、8375 和 3930 ha。粤桂琼三省区红树林面积合计达 21389 ha，占全国红树林总面积的 94.4%。福建省红树林面积为 615.1ha，台湾 287.0 ha，香港 263 ha，澳门 64.0 ha，浙江省仅有 20.6 ha。

从地理区域上看，中国的红树林集中生长在三个区域：1）海南岛东海岸。其中，东寨港有 1575 ha，清澜港有 1189 ha，两处红树林面积合计 2764 ha，占海南省红树林总面积的 70.3%，占全国红树林总面积的 12.2%。2）广东省湛江市沿岸。整个湛江市沿海红树林已合并成为一个国家级保护区，红树林面积达 7242 ha，占广东省红树林的 79.7%，占全国红树林总面积的 32.0%。3）广西北部湾海岸。广西北部湾沿岸的红树林面积 8375 ha，占全国红树林总面积的 37.0%。这三个区域的红树林面积合计 18380 ha，占中国红树林总面积的 81.2%，是中国红树林的主要分布区。

1.3 中国红树林生态健康状况和原因分析

1.3.1 中国红树林生态健康状况

不合理的开发活动已造成我国东南沿海大量原生红树林消失，群落普遍次生，林分质量不高，生态系统功能退化，生态服务价值总量锐减，危及近海渔业和养殖业[9]。

整体上我国红树林群落低矮，称之为灌丛并不为过。2001 年全国红树林资源调查数