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湖泊底泥藻积层特性及其内源污染风险影响研究

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摘要：通过对夏秋季节滇池湖滨藻积层全面系统调研以及湖区底泥内源释放通量研究,旨在厘清滇池藻类沉积特性及其对内源污染负荷贡献.基于全湖24个断面,96个剖面特征系统调研,发现滇池底泥藻类生物量续存由北向南逐步减轻,外海东部湖区贮存量远高于西部,其演变趋势与多年来滇池蓝藻水华空间分布异质特性相一致.全湖湖滨水域整体分布格局为:外海中部(577.92ng/g)>外海北部(521.32ng/g)>草海(276.55ng/g)>外海南部(240.05ng/g).滇池藻积层厚度范围基本维持在 5~10cm,其中深度 0~10cm 富集区域(即新鲜藻碎屑沉降富集区)占比约 27%,而集中在深度 10~15cm 富集区占比 25%以上.草海和外海北部表、中、下层叶绿素 a 含量没有明显差异,这与草海表层浮泥再悬浮过程以及外海北部常年风浪扰动下底泥再悬浮密切相关.经初步核算,草海底泥藻类生物量 3.65g/m^2,贡献了底泥藻源性氮磷分别为 26.4t 和 2.5t.外海 6.43g/m^2,贡献了底泥藻源性氮磷分别为 46.6 和 4.5t.底泥-上覆水界面处 SRP 平均释放速率为 2.45mg/(m^2·d),NH_4^+-N 平均释放速率为 138.21mg/(m^2·d),均以释放为主.外海北部、中部湖滨水域的 SRP 和 NH_4^+-N 释放速率高于草海、外海南部,这与藻积层分布特性高度吻合,这可能是滇池藻源性氮磷在更深程度上影响底泥氮磷释放主要证据之一.另外进一步分析发现滇池底泥 Chla 含量与 SRP、NH_4^+-N 释放速率呈显著正相关.滇池底泥内源释放风险呈现北高南低的空间差异,外海北部(藻类沉积量高及强扰动作用)和外海中部(藻类沉积量高)属内源氮磷释放高风险区,水域水质整体相对较差,底泥埋藏藻源性氮磷释放影响是其主要原因之一.草海及外海南部当前风险较低,但仍需加强管控监测.藻积层治理作为内源污染控制的关键环节,底泥藻源性氮磷富集与释放风险管控是今后滇池内源治理重点方向之一.

关键词：滇池；藻类沉积；底泥；内源；释放速率
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Accumulation characteristics of algae in lake sediments and their influence on the risk of internal pollution. GU Qian-qian[1], LI Yang[2], CAI Jian-xia[3], XIE Dong[1*], TONG Cheng-fei[3], GU Xiao-zhi[3], PAN Ji-zheng[3], CHEN kai-ning[3], FAN Cheng-xin[3] (1.School of Ecology and Environment, Nanjing Forestry University, Nanjing 210037, China；2.Kunming Dianchi and Plateau Lakes Institute, Kunming 650228, China；3.State Key Laboratory of Lake and Watershed Science for Water Security, Nanjing Institute of Geography and Lakes, Chinese Academy of Sciences, Nanjing 211135, China). *China Environmental Science*, 2025,45(12)：6659~6670

Abstract：Through comprehensive systematic surveys of algal accumulation layers along the shores of Dianchi Lake during summer and autumn, coupled with studies on the release flux of endogenous pollutants within the lake, this research aims to clarify the sedimentation characteristics of algae in Dianchi Lake and their contribution to endogenous pollution loads. Based on systematic surveys of 24 lake-wide cross-sections and 96 profile characteristics, it was found that the residual algal biomass in Dianchi Lake sediments gradually decreases from north to south. The storage volume in the eastern outer lake area is significantly higher than that in the western area, and this trend aligns with the spatial distribution heterogeneity of cyanobacterial blooms in Dianchi Lake over the years. The overall distribution pattern across the lake's littoral zone was: Central Outer Lake (577.92ng/g) > Northern Outer Lake (521.32ng/g) > Caohai (276.55ng/g) > Southern Outer Lake (240.05ng/g). The thickness of the algal layer in Dianchi Lake generally ranged between 5and 10cm. The 0~10cm depth zone (representing the fresh algal detritus settling and accumulation area) accounted for approximately 27% of the total thickness, while the 10~15cm depth zone contributed over 25%. No significant differences were observed in surface, middle, and bottom layer chlorophyll a concentrations between Caohai and the northern Outer Lake. This correlates closely with the resuspension of surface floc in Caohai and the year-round wind-wave disturbance causing sediment resuspension in the northern Outer Lake. Preliminary calculations indicate Caohai sediment algal biomass at 3.65g/m², contributing 26.4t and 2.5t of algal-derived nitrogen and phosphorus, respectively. In the outer lake, the biomass was 6.43g/m², contributing 46.6t

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and 4.5t of algal-derived nitrogen and phosphorus from the sediment, respectively. At the sediment-water interface, the average release rate of SRP was 2.45mg/(m²·d), and the average release rate of NH_4^+−N was 138.21mg/(m²·d), both dominated by release processes. SRP and NH_4^+−N release rates in the northern and central coastal waters of the outer lake were higher than those in Caohai and the southern outer lake, closely aligning with algal accumulation layer distribution characteristics. This may serve as primary evidence that algal-derived nitrogen and phosphorus in Dianchi Lake profoundly influence sediment nitrogen and phosphorus release. Furthermore, analysis revealed a significant positive correlation between Chla content in Dianchi sediment and SRP/NH_4^+−N release rates. The risk of endogenous release from Dianchi Lake sediments exhibits spatial variation, being higher in the north and lower in the south. The northern Outer Lake (high algal deposition and strong disturbance) and central Outer Lake (high algal deposition) are high-risk zones for endogenous nitrogen and phosphorus release, characterized by relatively poorer overall water quality. The release of algal-derived nitrogen and phosphorus from buried sediments is one of the primary contributing factors. The southern parts of Caohai and the outer lake currently exhibit lower risks but still require enhanced management and monitoring. As a critical component of endogenous pollution control, managing the enrichment and release risks of algal-derived nitrogen and phosphorus in sediments will be a key focus for future endogenous pollution control in Dianchi Lake.

Key words：Dianchi；algal deposition；sediment；endogenous；release rate

底泥是湖泊水体氮磷等物质重要储库和内在污染源.研究表明,滇池底泥中含有较高水平的有机物以及丰富的氮、磷、重金属和有机污染物,这些污染物的含量在与太湖和巢湖的比较中显得尤为突出[1-3].特别是在泥水交界的表层区域,氮和磷的浓度出现显著的升高现象,这些区域的污染物浓度超过了其上方水体及下方底泥孔隙水中的浓度,促使污染物向水体上层扩散,从而对水质产生负面影响[4].滇池底泥中的氮、磷并没有与水体上层达到平衡状态,而是持续不断地释放,这一持续的释放过程进一步加剧了水质的恶化.

湖泊沉降藻类在底泥中沉积与埋藏过程对湖泊底泥内源污染负荷起到至关重要作用.沉积物不仅能反映水体区域环境的变迁和水体的类型,同时也是生源要素,特别是氮、磷的重要存储库,对湖泊中营养元素的循环有着重要意义[5].受西南风、西风和南风影响,夏秋季滇池大量藻类水华在滇池北岸湖湾和东岸湖滨积聚[6].在水体藻类“昼浮夜沉”节律特性加持下,有大量过剩的藻类在湖滨水下沉积、腐解后,其残体碎屑中胶体失去稳定后发生凝聚形成絮凝体、团块,在重力作用影响下发生沉积,滇池局部水域底泥藻类沉积显著,埋藏较浅,在水−沉积物界面与水生高等植物残体以及外源输入的有机质混合堆积形成滇池水污染潜在风险较大的藻积层[7]. 据报道新鲜藻类约含氮2.8%,含磷 0.075%,1t 新鲜藻类衰亡沉降,可以增加湖泊表层沉积物中 2.8kg 氮和 0.76kg 磷[8],其中磷主要以溶解态正磷酸盐形式存在,氮形态主要以氨氮等无机氮为主[9].当环境条件发生变化时(如水温升高、缺氧、pH 值变化等),沉积物中的营养物质再次释放到水体中[10].底泥中藻源性氮磷富集与再释放是滇池水体氮磷的重要供给源之一.

沉积物参与的内源释放及营养物内循环持续地阻碍湖泊水质净化和生态恢复[11].近年来,有很多学者对滇池沉积物中营养盐进行研究.陈永川等[12]对滇池沉积物总氮含量进行时空变化研究,结果表明呈现明显的季节变化和空间差异,整体趋势为夏季高,冬季低,沉积物厚度较深的地方,总氮含量也高.吴亚林等[13]对滇池沉积物氮的组成、分布以及埋藏特征进行探讨,结果表明沉积通量最高值为1.287mg/(cm^2·a),TN 埋藏量可达 92139.15t,内源氮负荷问题日益严重.沉积物孔隙水和上覆水之间的浓度梯度决定了沉积物对水体营养物质的贡献能力[14].研究发现[15],滇池沉积物间隙水中平均 NH_4^+−N 浓度(12.1mg/L)显著高于上覆水(3.2mg/L),沉积物释放是水体营养物质的重要来源.根据昆明市环科院 2013 年对滇池全湖污染层氮磷含量及其释放情况的研究结果,滇池沉积物中总氮释放负荷可达每年 2252t,总磷释放负荷可达每年 18.41t.内源释放对于滇池富营养化管控不容忽视,沉积物的管理与治理是滇池水质改善的关键问题.

藻类沉降后与底泥中黏土、粉砂、有机碎屑等其他物质相互结合,最终沉积在沉积物表面,经长期积累逐渐形成藻积层.藻积层是滇池内源污染的重要来源,其富集的藻类分解会释放大量氮磷等营养盐,加剧水体富营养化,导致蓝藻水华频发.研究藻积层的分布和特性,有助于精准控制内源污染,改善滇池水质.藻积层的形成和分解破坏了生态平衡,对底栖生物和水生植物构成威胁,藻积层治理是内源污染控制的关键环节,本文通过对全湖底泥藻积层富集特

性、埋藏关键层位及赋存量关键因子的全面解析,同时结合全湖底泥氮磷污染特征及其对泥−水界面释放规律影响研究,旨在厘清湖泊藻积层在底泥内源污染负荷中的影响规律及潜在贡献.可为我国湖泊底泥内源污染精准治理和科学治理提供科技支撑.

1　材料与方法

1.1　研究区概况与样品采集

滇池位于云南省昆明市的西南部,隶属于长江水系金沙江流域.滇池流域属亚热带季风气候,流域内雨旱季分明,85%的降水发生在雨季(5~10 月),流域内多年降水量 924.70mm,但年际间浮动较大(553.60~1234.10mm)[16-17].湖体呈弓形,弓背向东,南北长约 32km,东西宽 12.5km,湖岸线长 163.2km,平均深度 5.3km,最大深度 11.2km;滇池南北分为草海、外海两部分,其中草海占滇池总面积的 3.6%,外海为滇池主体部分,占滇池总面积的 96.4%[18].

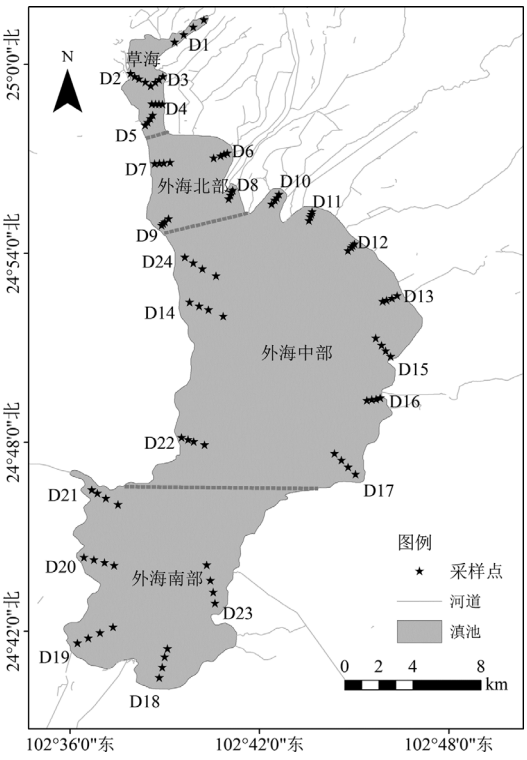


图 1　研究点位布设

Fig.1　Research site layout

本研究于 2024 年 7 月在滇池藻类重点防控区、藻类主要分布区以及开阔水域开展监测,原则上在湖畔形态、底质类型和水生植被发生变化的区域布点采样.自岸边向湖心方向,每隔 2km 设置采样点,采用沉积物柱状扰动的沉积物−水柱状样品,并采集该点位的原位湖水.本次采样布设 24 个断面,每个断面设置 4 个样点,共 96 个;现场按 5cm 分层,分为表、中、下三层(图 1).

1.2　样品分析与数据处理

1.2.1　样品指标测定　取一定量经冷冻干燥后的底泥样品,去除样品中的砂石和动植物残体,研磨过 150 目尼龙分样筛,称取 1g 底泥放入研钵中,加入 2~3mL90%丙酮溶液研磨 2~5min 且充分混匀后转移至 10mL 具塞离心管中,静置于低温(4℃)黑暗条件下提取 8~10h,然后用 90%丙酮溶液将所得上清液定容至 10mL 待测.最后用荧光分光光度计测定待测液中叶绿素 a 含量.底泥中有效态氨氮测定方法采用氯化钾溶液提取−分光光度法(HJ634−2012)[19];有效态磷的测定采用碳酸氢钠浸提−钼锑抗分光光度法(HJ704−2014)[20];底泥中总氮(TN)采用碱性过硫酸钾氧化紫外分光光度法测定(GB11894-1989)[21];总磷(TP)采用钼锑抗分光光度法测定(GB11893−1989)[22],有机质含量采用经典重铬酸钾法测定[23];含水率采用烘干法测定.

1.2.2　氮磷释放试验　本实验利用室内的沉积物−水界面静态释放实验.利用虹吸法除去柱状样中原有的上覆水,然后再用虹吸法沿壁缓慢注入该采样点的原位湖水,至液面高度距沉积物表面 20cm 处停止(此时水柱体积为 1134.3mL).模拟原环境遮光进行静态恒温培养实验,实验初始,每 12h 取一次水样,每次取样体积为 50mL,同时用原样点初始过滤水样补充至刻度以保持水量平衡,全部实验于 72h (3d)止,采集后的水样按照《水质样品的保存和管理技术规定》(HJ 493−2009)中的方法保存,用于以后的测定.测定指标包括氨氮 NH_4^+−N 和可溶性反应磷 SRP.根据公式计算释放速率[24]:

$$R=\frac{[V\times(C_n-C_0)+\sum_{j=1}^{n}V_{j-1}(C_{j-1}-C_2)]}{S\times t} \quad (1)$$

式中:R 为释放速率,mg/(m^2·d); V为柱中上覆水体积,L;C_n、C_0、C_{j-1} 分别为第 n 次、0 次(即初始)和 j−1 次采样时某物质质量浓度,mg/L; V_{j-1} 为第 j−1 次采样体积,L;C_a 为添加水样中的物质含量,mg/L,S 为柱样中水−沉积物接触面积,m^2;t 为释放时间,d.

1.2.3　数据处理与分析　使用 Excel 2016 进行实验数据汇总、统计,藻积层和营养物质空间分布由反距

离加权插值法基于全湖 96 个采样断面网格插值获得.统计分析使用 SPSS26 分析,通过单因素方差分析(ANOVA)以评估组间差异的显著性(P<0.05).图表绘制借助于软件 Origin2017 和 ArcGIS10.5.

2 结果与分析

2.1 藻积层藻类含量空间分布特征

2.1.1 底泥藻积层分布总体格局及变化趋势 通过对滇池草海及外海区域底泥中的藻类含量进行空间分布分析(图 2(a)),结果表明,草海与外海的藻类含量存在显著差异,草海的藻类含量总体低于外海,外海自北向南呈现出逐渐降低的变化趋势.草海的叶绿素 a 含量变化范围为 7.18~1052.77ng/g,平均值为 291.01ng/g;外海北部和中部的叶绿素 a 含量变化范围分别为 54.76~1326.19ng/g 和 5.18~1666.7ng/g,平均值分别为 521.32ng/g 和 562.54ng/g.而外海南部的叶绿素 a 含量处于最低水平,变化范围为 7.18~941.1ng/g,均值为 240.05ng/g.结合叶绿素 a 含量最大值在各层的占比来看(图 2(b)),外海中部表层占比最大,为 70%,外海南部下层占比最大,为 78%.这表明草海和外海北部表、中、下层叶绿素含量没有明显差异,外海南部底泥藻类含量有明显的历史沉积现象.

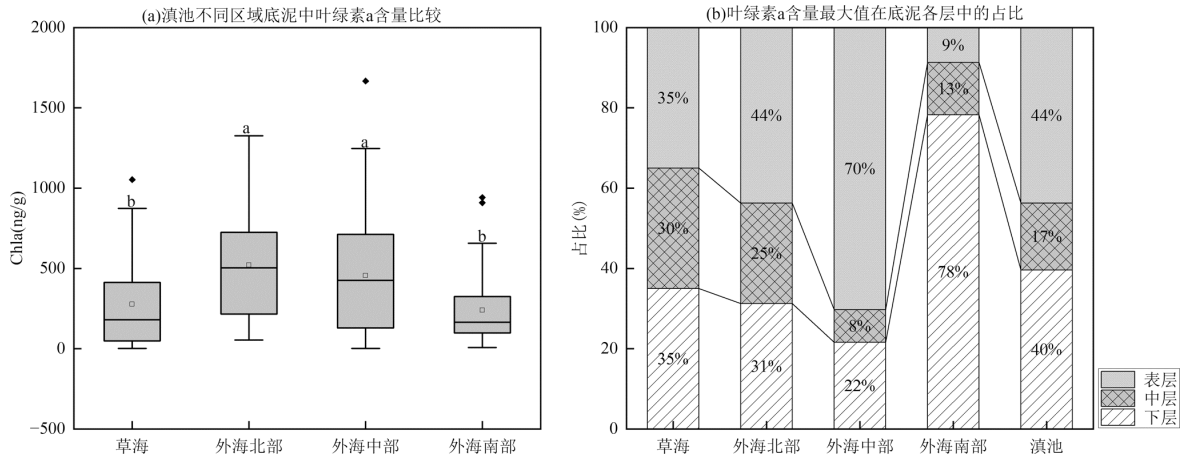


图 2 滇池不同区域底泥中叶绿素 a 含量与最大值在底泥各层中的占比

Fig.2 Chlorophyll a content in bottom sediments across different regions of Dianchi Lake and its proportion relative to the maximum value in each sediment layer

不同小写字母表示滇池不同区域底泥中叶绿素 a 含量差异显著(P<0.05)

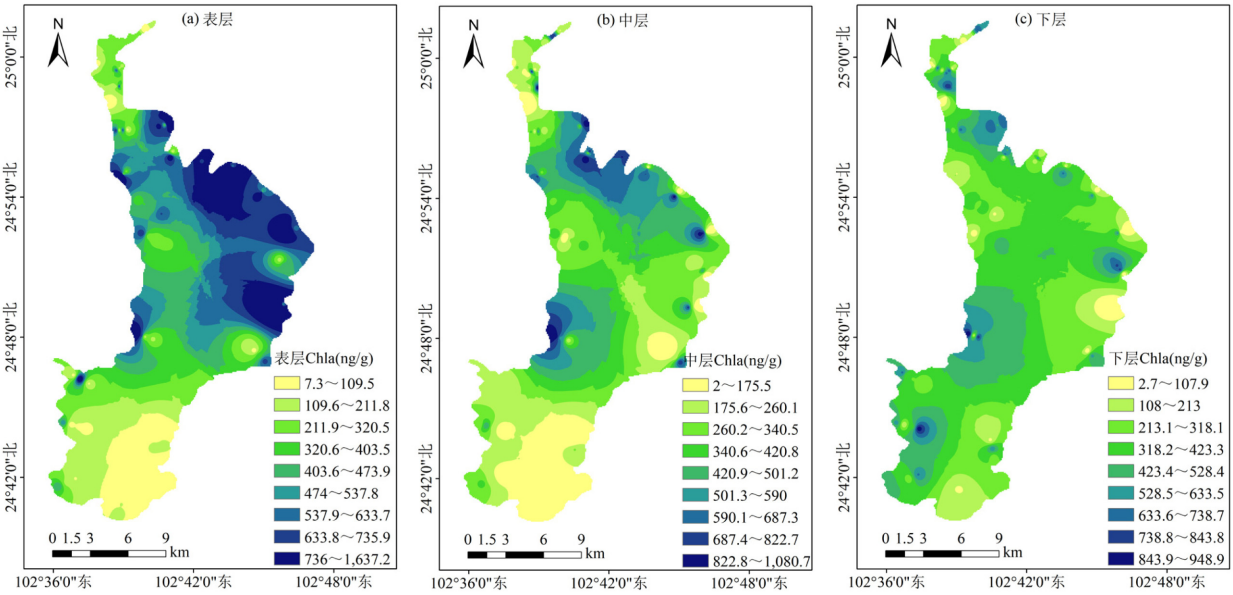


图 3 滇池底泥叶绿素 a 含量空间分布

Fig.3 Spatial distribution of Chlorophyll a concentration in dianchi Lake sediment

2.1.2　藻积层藻类含量空间分布特征　滇池底泥藻类含量空间分布特征较为显著(图 3).滇池表层底泥(0~5cm)叶绿素 a 含量分布具有显著空间异质性,高含量区域主要集中在外海北部和中部湖区,藻类有机碎屑与其分解物质高度聚集于东部,平均浓度高达 870ng/g.中层底泥(5~10cm)叶绿素 a 含量与表层底泥藻含量分布集中区相似,大体上中层底泥叶绿素 a 含量与表层相比,骤减趋势明显,藻类聚集区域逐步倾向西部与北部,尤其是南边西侧湖区叶绿素 a 含量高于表层底泥.下层底泥(10~15cm)叶绿素 a 含量全湖分布较为均匀,草海南部和外海南部的藻类含量较表层和中层均有所升高.通过对表层、中层和下层比较分析(图 4),结果显示,草海和外海北部表、中、下层底泥中叶绿素 a 含量没有明显差异,外海中部表层叶绿素 a 含量显著高于中层和下层,外海南部下层叶绿素 a 含量显著高于表层和中层.

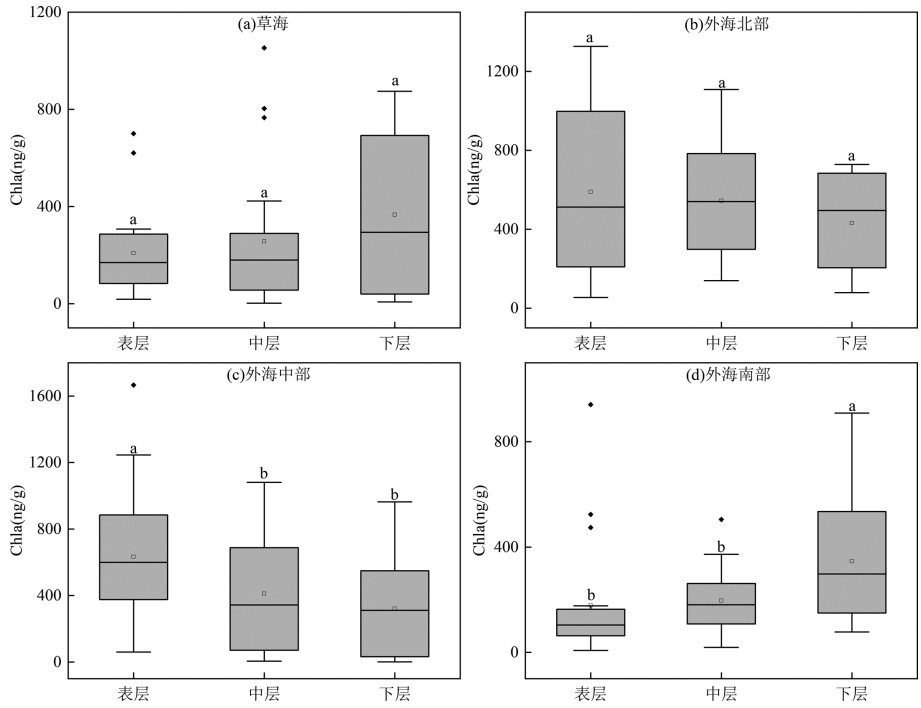


图 4　底泥中叶绿素 a 含量比较

Fig.4　Comparison of Chlorophyll a content in sediment

不同小写字母表示底泥中叶绿素 a 含量差异显著(P<0.05)

2.2　滇池底泥理化特性

滇池外海和草海底泥的理化特性如图 5 所示.整体来看,外海总磷平均含量为 1.439mg/g,高于草海 1.361mg/g;但有机质和总氮分布趋势刚好相反,草海底泥中有机质(30.36%)和总氮(5.659mg/g)均远高于外海(分别为 12.83%和 4.559mg/g).另外从表层底泥含水率来看,草海表层底泥含水率普遍较高,含水率范围分布在 81%~87%之间,均值为 85%,属于流体状浮泥为主.外海底泥含水率在 50%~89%之间,均值为 75%.外海有效态氨氮变化范围为 0.06~0.27mg/g,草海变化范围为 0.03~0.14mg/g,外海有效态氨氮平均含量为 0.12mg/g,草海为 0.08mg/g,外海高于草海.外海有效态磷含量平均值为 0.24mg/g,高于草海(均值为 0.05mg/g).

2.3　营养物质释放速率

静态培养过程中,底泥−上覆水界面处 SRP 释放速率在 0.28~7.42mg/(m^2·d)之间(图 6),平均释放速率为 2.45mg/(m^2·d),以释放为主.其中,外海中部 SRP 释放速率(4.68±2.32)mg/(m^2·d)显著高于(P<0.05,ANOVA)外海南部(1.34±0.39) mg/(m^2·d),草海和外海北部之间没有明显差异.底泥−上覆水界面处 NH_4^+−N 释放速率在−11.62~220.45mg/(m^2·d)之间,平均释放速率为 138.21mg/(m^2·d),以释放为主.外海北部 NH_4^+−N 释放速率(153.83±32.52)mg/(m^2·d)显著高于草海(63.46±28.43)mg/(m^2·d)和外海南部(30.94±18.26)mg/(m^2·d).总之,外海北部、中部的 SRP 和 NH_4^+−N 释放速率高于草海、外海南部,表现出显著的空间差异.结合滇池底泥 Chla 含量空

间分布来看,推测滇池底泥 SRP 和 NH_4^+-N 释放速率受到底泥 Chla 含量的影响,通过进一步做 Pearson 相关性分析和线性回归,结果显示(图 7),SRP 释放速率与底泥 SRP 含量呈正相关、NH_4^+-N 释放速率与底泥 NH_4^+-N 含量呈正相关,SRP、NH_4^+-N 释放速率均与 Chla 含量呈显著正相关,表明滇池底泥 Chla 含量是影响底泥 SRP 和 NH_4^+-N 释放速率的重要因素.

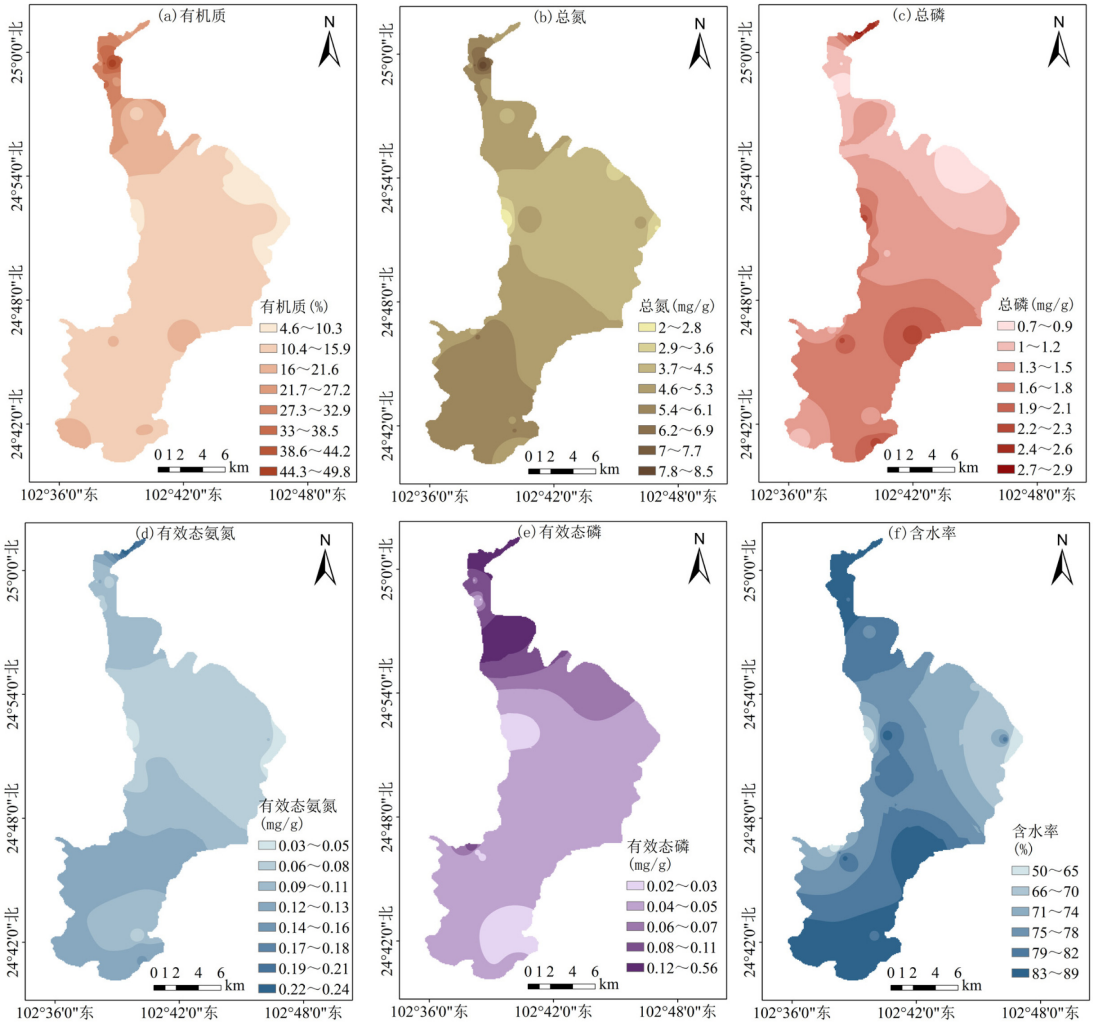


图 5 滇池底泥理化特性空间特征

Fig.5 Spatial characteristics of physicochemical properties of Dianchi Lake sediment

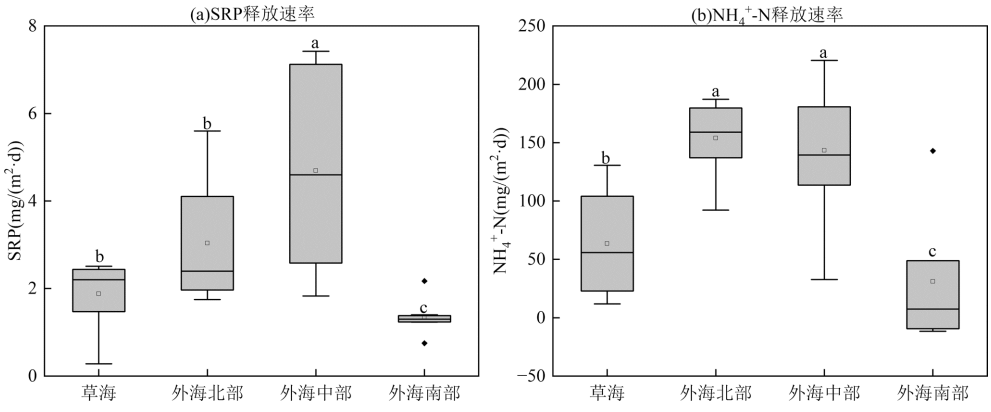


图 6 滇池不同区域底泥 SRP、NH_4^+-N 释放速率比较

Fig.6 Comparison of SRP and NH_4^+-N release rates in sediments from different areas of Dianchi Lake

不同小写字母表示滇池不同区域底泥释放速率差异显著(P<0.05)

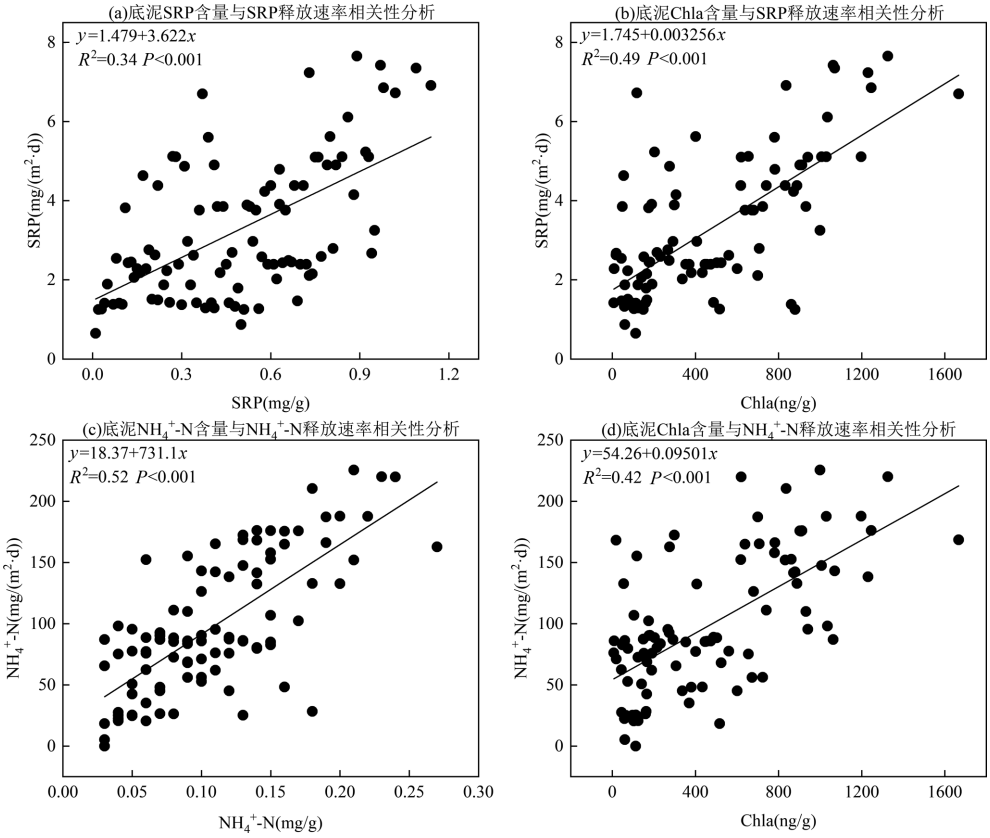


图 7　底泥 SRP、NH_4^+–N 释放速率与底泥 Chla、SRP、NH_4^+–N 含量的关系

Fig.7　Relationship between sediment SRP, NH_4^+–N release rate and sediment Chla, SRP, NH_4^+–N content

3　讨论

通过对滇池藻积层空间格局进行分析,结果表明,滇池外海沉积物藻类含量总体有着明显的空间特点:由北向南逐渐减少,外海北部和中部主要集中在东部水域.这可能与滇池春夏季以盛行西风、西南风和南风为主有关,导致浮游植物在北岸岸线和东岸岸线、西部零散湖湾聚积.已有研究表明,由风驱动的水流和藻类运动可能会导致藻类的聚集或分散[25-26],风向能影响藻类堆积聚集,影响紊流扰动进而直接影响藻类输移,并通过直接或间接作用影响藻类生长[27],风速可通过改变湖泊内部垂向扰动和物质通量从而影响湖体内的化学和生物过程[28].此外,从藻积层藻类含量的垂向分布来看,外海中部和外海南部底泥藻类含量有明显的分层和历史沉积现象, 这可能与滇池不同区域水体滞留时间有关. 以往研究结果表明, 滇池北部入湖河流占总入湖水量的 84.9%,而中部和南部仅占 15.1%[6],因此中部和南部入湖河流的稀疏可能导致了水体滞留时间较长, 从而导致底泥藻类含量有明显的分层和历史沉积现象. 目前许多研究者都认为,夏季藻类水华的发生与冬季沉积物中越冬藻类有密切关系[29-30].湖库沉积物作为浮游藻类“休眠”的场所,为藻类的再次增殖提供“种源”,也为在湖库表面形成水华提供一定的条件[31-32].一部分学者认为在生物扰动的作用下会使藻类细胞向底泥更深处迁移,或底泥中存在大量微生物细菌以底泥藻类为食,降低底泥藻类复苏几率,绝大多数底泥藻类在表层的复苏量最高[33]. 因此,滇池外海北部和中部夏季藻类暴发的风险更高.此外,在同等条件下,近岸带藻类更容易复苏[34]. 这与本研究藻积层分布趋势相一致,说明底泥来源(近岸/敞水区)也是间接影响藻类复苏的重要因子.

从全湖空间分布格局来看,外海和草海的总氮含量均较高,其中,总氮平均含量为 4.80mg/g.这可能受地域影响,属于静水性湖泊,自净能力差,水体交换速率低.另外受水体常年聚集藻类影响,草海及外海北部湖区多为滇池藻类部分集聚区,导致大量的藻类沉降在湖底沉积,沉积物总氮及有机质含量也相应较高.湖泊中总磷含量的变化趋势与总氮刚好相反,这与滇池底泥总磷以无机磷为主高度相关.结合

采样时间、天气状况以及采样点地形特征(大面积无植被覆盖的红黄壤山坡),主要是夏季降雨量较大,容易形成明显的地表径流,使山体水土流失严重,进而使大量易溶解性磷径流进入水体.结合湖泊水体沉积学理论,可能原因有:(1)滇池地区常年盛行西南风,水体中总氮、总磷随水流和风的扰动向北部聚集,(2)与滇池特定的水动力、地形构造有关,显然秋季中有效磷的占比含量大幅度增加,促进了底泥中磷的释放.高密度蓝藻聚集后易死亡并且形成有机碎屑,一部分蓝藻碎屑在水体表层被好氧异养微生物利用[35],大部分蓝藻碎屑沉降至沉积物表面,其分解会导致沉积物碳、氮、磷含量增加[36-38].大量研究发现,沉积物内源氮磷营养盐的释放是导致湖泊富营养化的主要原因[39-41].滇池属半封闭式湖泊,换水周期长,水底藻积层藻类分解是滇池局部水体短期内水体 COD 超标主要诱因之一[42].滇池底泥藻类多聚集埋藏于东部湖滨或下风口湖湾,研究表明,藻类残体沉降到水-沉积物表面,大量聚集形成丰富的藻类有机质,藻体含碳量达 30%~50%,可在夏秋季节 10d 左右分解达到峰值[43].部分微囊藻好氧降解过程释放的溶解态总磷占水体总磷的 50%左右,造成水体恶化[44].由藻类死亡分解向沉积物中释放出的氮磷,沉积物可能还会释放出来,为藻类的下一阶段的生长在此提供营养物质,循环往复,使得滇池藻类生长与沉积物中的营养物质相互作用,因此要及时对藻类的生长进行管控,减少潜在营养源.此外,滇池治理应考虑其沉积物污染特征,应分区、分级、分期治理其沉积物营养负荷.

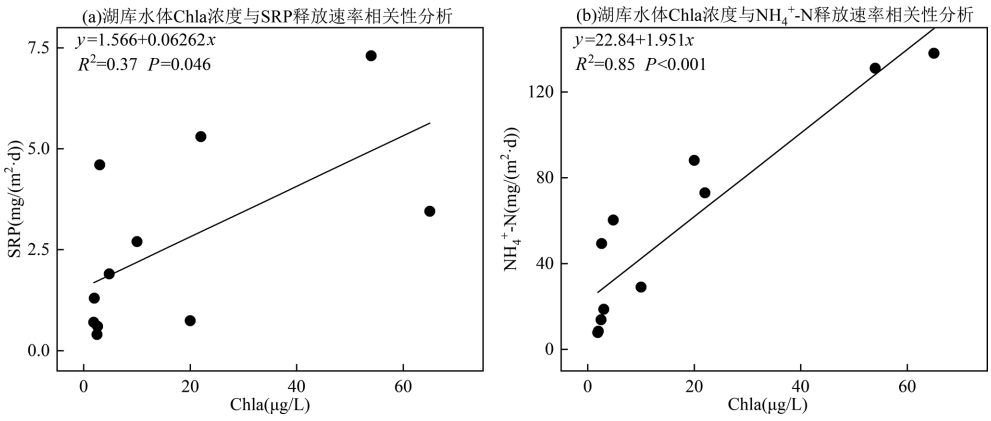


图 8 湖库水体 Chla 浓度与 SRP、NH_4^+-N 释放速率的关系

Fig.8 Relationship between Chlorophyll a concentration and SRP and NH_4^+-N release rates in reservoir water bodies

本研究显示,外海中部 SRP 释放速率显著高于外海南部,而 NH_4^+-N 释放速率在外海北部最高,草海和外海南部较低.这种空间异质性可能与不同区域的植被、水动力条件、底泥理化性质、微生物群落结构、藻类活动等有关[45].外海北部底泥有机质和总氮含量较高(图 5),为微生物矿化作用提供了充足底物,从而加速 NH_4^+-N 的生成与释放;外海中部底泥总磷含量较高,且以易释放的无机磷为主,在厌氧条件下更易转化为 SRP.Pearson 相关性分析证实,Chla 含量与 SRP、NH_4^+-N 释放速率呈显著正相关,滇池底泥表层藻类的富集导致了 SRP、NH_4^+-N 释放速率升高,该研究结果与以往研究一致.在 Yin 等人的培养实验中[46],巢湖底泥中的藻类 Chla 含量与磷通量呈显著正相关.Chen 等[47]人研究表明藻类沉积会在短期内(第 0~3d)造成上覆水中 SRP 浓度快速增加.王亚蕊等[48]人同样发现,藻类堆积会增强底泥需氧量,加快底泥与水之间氮磷营养盐、DOC 循环,并且上覆水中氮磷增加浓度与沉积藻类密度呈正比.尽管季节性波动会导致藻类生长速率和短期降解活性的变化,但藻类沉积降解影响的内源释放主要受长期累计效应调控.通过国内主要湖库及世界上其它湖库底泥内源释放特性与叶绿素综合分析发现:底泥 SRP、NH_4^+-N 释放速率与水体中 Chla 浓度呈显著正相关(图 8).因此,进一步说明了藻类沉积与缓慢降解会改变内源释放的进程,是内源释放的关键途径,并且这一过程中短期波动对于长期释放趋势的影响相对有限.此外,本研究测得的 SRP 释放速率(0.28~7.42mg/(m^2·d))与国内外其他富营养化

湖泊(如太湖、巢湖)的相关研究范围相近,但NH_4^+−N释放速率(最高达 220.45mg/(m^2·d))显著高于多数湖泊,这可能与滇池长期的高氮负荷和底泥藻源性有机质积累有关.其中,底泥 Chla 含量对 SRP、NH_4^+−N释放速率在外海北部和中部尤为显著,可针对性采取控藻和底泥修复措施,建议在藻类常年沉降水域加强生物调控,通过增殖滇池生态系统内本土物种,包括底栖生物(如滇池圆田螺)和滤食性鱼类(如滇池金线鲃、昆明裂腹鱼、昆明高原鳅≥40g/m³).优化碎屑食物链,降低杂食性鱼类密度.底栖生物可直接清除藻类残体(摄食效率 30%~50%),搭配河蚬控制悬浮藻类和有机碎屑[65].另外滇池底泥沉降藻类是早春水体藻类复苏主要来源之一.尤其在北部和东部蓝藻沉降重灾区,也是常年风浪动力扰动较大水域,底泥再悬浮对底泥藻类的垂直迁移有重要的影响.建议通过加大水下植被恢复力度增强表层底泥稳定性,实施局部水下地形改造,改善水底湖流紊流和湍流扰动,减少底泥再悬浮,从而实现滇池底泥蓝藻深度治理与防控.

表 1　滇池与其他水体底泥 N 和 P 营养盐释放速率比较

Table 1　Comparison of nitrogen and phosphorus nutrient release rates from sediments in Dianchi Lake and other water bodies

湖库名称	NH_4^+−N 释放速率 (mg/(m^2·d))	SRP 释放速率 (mg/(m^2·d))	水体中 Chla 浓度(μg/L)
太湖[49−50]	−11~56.9(29.0)	−4.56~25.2(2.7)	10.0
抚仙湖[51−52]	2.1~13.7(7.8)	0.4~1.1(0.7)	1.9
巢湖[53−54]	14.2~128.3(73)	0.1~13.0(5.3)	22.0
丹江口水库[55−56]	13.07~24.88(18.7)	3.06~6.02(4.6)	3.0
于桥水库[57−58]	20.6~250.5(131.0)	1.1~13.3(7.3)	54.0
周村水库[59−60]	62.8~133.2(88.1)	0.4~1.3(0.7)	20.0
杜塘水库[61]	56.7~82.9(60.3)	1.6~2.4(1.9)	4.8
大黑汀水库[62]	3.5~110.5(49.3)	0.1~1.6(0.6)	2.6
日本 Biwa Lake[63]	3.8~17.99(8.5)	0.2~2.59(1.3)	2.0
澳大利亚 Suma Park 水库[64]	11.3~17.25(13.8)	0.27~0.55(0.4)	2.5
滇池	−11.62~220.45(138.2)	0.28~7.42(3.4)	95.0

4　结论

4.1　滇池藻积层藻生物量沉积与埋藏存在显著的地域性差异.底泥藻类生物量续存由北向南逐步减轻,其演变趋势与多年来滇池蓝藻水华空间分布异质特性相一致.

4.2　滇池表层(0~15cm)底泥是藻积层富集活性层.外海表、中层藻类生物量在湖滨带和东部水域较为集中.草海和外海北部表、中、下层叶绿素 a 含量没有明显差异.滇池整体底泥藻类生物量在 3.65~11.11g/m^2 波动,外海明显高于草海,经核算藻积层贡献了底泥藻源性氮磷分别为 46.6 和 4.5t.

4.3　底泥内源释放速率整体空间特征主要表现为外海北部、高于草海和外海南部. 滇池底泥藻积层 Chla 含量与 SRP、NH_4^+−N 释放速率呈显著正相关,滇池底泥藻类沉降和垂向埋藏特性是影响底泥污染活性层SRP和NH_4^+−N释放速率的重要驱动因素.也是驱动底泥埋藏藻源性氮磷释放影响是其重要原因之一.

4.4　滇池底泥藻积层研究对于滇池的综合治理和水环境持续改善具有不可替代的价值.底泥富集的藻积层治理是内源污染控制的关键环节,底泥藻积层的藻源性氮磷富集与释放风险管控是今后滇池内源治理重点方向之一.

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