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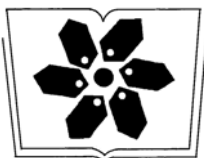
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生态学报

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封面图说: 秋色藏野驴群——秋天已经降临在海拔4200多米的黄河源区, 红色的西伯利亚蓼(生于盐碱荒地或砂质含盐碱土壤)铺满大地, 间有的高原苔草也泛出了金黄, 行走在上面的藏野驴们顾不上欣赏这美丽的秋色, 只是抓紧时间, 在严冬到来之前取食, 添肥增膘以求渡过青藏高原即将到来的漫长冬天。

彩图提供: 陈建伟教授 北京林业大学 E-mail: cites.chenjw@163.com

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臭氧浓度升高对香樟叶片光合色素及 抗过氧化的影响及其氮素响应

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摘要:为阐明氮(N)沉降条件下我国亚热带典型常绿树种香樟(*Cinnamomum camphora*)的臭氧(O₃)胁迫响应特征,以1年生幼苗为试验对象,采用开顶气室(OTC)进行模拟研究。O₃处理设大气O₃(AA)、大气O₃+60 nmol/mol(AA+60)、大气O₃+120 nmol/mol(AA+120)3个水平;N素以硝酸铵(NH₄NO₃)溶液形式施加,施N量设0(N0)、30(N30)、60(N60)(kg·hm⁻²·a⁻¹)3个水平。主要考察了叶片膜质过氧化、光合色素、胞质抗坏血酸含量及总抗氧化能力的胁迫响应特征。结果表明:一个生长季(2009年5月15日—2009年9月10日)高浓度O₃处理导致试验幼苗叶肉细胞膜脂过氧化程度显著加剧,叶绿素a、叶绿素b、类胡萝卜素含量显著降低;N素施加显著提高了叶绿素含量,但未改变细胞膜脂过氧化水平。叶片总抗氧化能力在AA+120处理下显著提高,但未受N施加影响。还原型抗坏血酸含量在N0处理下随O₃浓度升高而降低;在N30及N60处理下随O₃浓度升高而增高。施N可通过提高叶片抗坏血酸含量来增强香樟对O₃升高的适应能力。研究结论可为O₃与N复合污染下,我国亚热带地区典型常绿树种的保护提供科学参考。

关键词:香樟;膜质过氧化;叶绿素;抗坏血酸

Effects of elevated ozone on foliar chlorophyll content and antioxidant capacity in leaves of *Cinnamomum camphora* under enhanced nitrogen loads

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Abstract: Elevated tropospheric ozone (O₃) and enhanced atmospheric nitrogen (N) deposition exert great impact on the physiology of forest trees. The respective effects of these two pollutants have been studied thoroughly during the past couple of decades. However, little information is available concerning their combined effects on the physiology of subtropical evergreen trees. In the present study, O₃ effects on *Cinnamomum camphora*, a native evergreen tree species, widely distributed in subtropical region, were investigated under enhanced N loads. One-year-old seedlings were adopted and the experiment was carried out in open-top chambers (OTCs). O₃ fumigation regimes were set at ambient air (AA), ambient air plus 60 nmol/mol (AA+60) and ambient air plus 120 nmol/mol (AA+120); N load levels were set at 0 (CK), 30 and 60 kg·hm⁻²·a⁻¹, designated as N0, N30 and N60, respectively. Membrane lipid peroxidation, foliar chlorophyll and ascorbic acid contents as well as the total antioxidant capacity were examined after treatments for one growing season (May 5-September 10, 2009). Foliar MDA (malondialdehyde) concentration was significantly enhanced by AA+120 treatment,

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but changed little in AA+60. Neither N30 nor N60 affected foliar MDA concentration significantly. Chlorophyll a content significantly decreased under both AA+60 and AA+120 treatments, and was significantly lower in the latter than in the former. Both N30 and N60 significantly increased chlorophyll a content, and the increment under N60 was significantly greater than that under N30. Chlorophyll b was also significantly increased by both N30 and N60, while was only significantly decreased by AA+120 rather than by AA+60. AA+120, as well as N60, significantly decreased chlorophyll a/b, which, however, was affected by neither AA+60 nor N30. The effects of elevated O_3 and enhanced N on foliar carotenoid content were similar to those on Chlorophyll a content: significant treatment effects (O_3 and N) with significant differences between treatment levels (AA+60 and AA+120, or N30 and N60). Besides, AA+120 significantly increased the total antioxidant capacity, on which, however, the effect of AA+60 was not significant. Significant difference of the total antioxidant capacity was not found either between AA+60 and AA+120, or among the N treatments. There were no significant interactions detected between O_3 and N on foliar MDA, chlorophyll content and the total antioxidant capacity in our study. However, the effects of elevated O_3 on the reduced (ASC) and total ascorbic acid ([ASC+DHA]) content were significantly modified by N loads. Under N0, both AA+60 and AA+120 significantly reduced the foliar ASC content, which, however, was significantly increased by AA+120 under N30 and N60. AA+60 also tended to increase the ASC content under enhanced N, although its effect was not significant. The effects of elevated O_3 on [ASC+DHA] under different N loads were similar to those on ASC, although they were of no statistical significance. Enhanced N loads strengthened the tolerance of *C. camphor* to O_3 through increasing the foliar ASC content.

Key Words: *cinnamomum camphora*; membrane lipid peroxidation; chlorophyll; ascorbic acid

地表臭氧(O_3)浓度升高是全球变化的重要方面,高浓度 O_3 对地表植被特别是森林生态系统具有很强的毒害作用^[1]。工业革命以来,大气 O_3 浓度已经升高了 36%;目前,全球近 1/4 的国家和地区面临着夏季对流层 60 nmol/mol 以上的 O_3 威胁^[2]。虽然近十年来北美和欧洲地表 O_3 浓度趋于持平甚至有所下降^[3],但以东南亚及非洲为代表的后起工业化地区 O_3 浓度将持续上升,对该区及全球生态安全构成严重威胁^[4]。到 2020 年,中国中东部大部分地区白天 O_3 平均浓度将达到 70 nmol/mol^[5],小时浓度最大值将超过 140 nmol/mol^[6]。同时,东南亚地区平均氮(N)沉降水平为 22 kg·hm⁻²·a⁻¹,最大沉降值超过 50 kg·hm⁻²·a⁻¹^[7],高于 10—20 kg·hm⁻²·a⁻¹ 的森林生态系统 N 承载阈值^[8]。过度 N 输入导致土壤酸化,生态系统营养失衡,生物多样性降低等^[9-11]。

O_3 主要通过气孔进入植物体内^[12],并与叶片内部氧化还原系统发生反应生成超氧阴离子自由基(O_2^-)、羟自由基($\cdot OH$)、过氧化物自由基($ROO\cdot$)以及过氧化氢(H_2O_2)等一系列活性分子^[13]。这些活性分子进一步启动或者介导下游氧化裂解^[4],并引起膜脂过氧化^[14]、叶绿素降解^[15]及植物体抗氧化物质如抗坏血酸^[16]等含量及组成发生变化。这些变化构成植物叶片伤害症状、光合抑制、生物量下降^[17]等 O_3 胁迫的生理基础。另一方面,N 施加可以促进冷杉(*Abies fabri*)、冬青栎(*Quercus ilex*)等幼苗胞质氧化抗性增强,叶肉细胞膜脂过氧化程度减轻^[18-19];然而,在一项针对不同施 N 条件下西瓜(*Citrillus lanatus*) O_3 胁迫效应的研究中,Calatayud 等发现高 N 处理显著加剧了 O_3 胁迫导致的膜脂过氧化^[20]。N 施加对植物叶片膜脂过氧化的影响因植物种类不同而存在差异。

目前, O_3 对树木胁迫的研究主要集中于暖温带落叶、针叶树种以及地中海常绿硬叶树种等^[21]。大量试验研究表明,不同树种抵抗 O_3 胁迫的能力存在差异,被子植物较裸子植物更为敏感^[22],地中海常绿树种较落叶、针叶树种耐性更强^[23]。国内学者利用开顶气室对 O_3 胁迫下银杏(*Ginkgo biloba*)、油松(*Pinus tabulaeformis*)、蒙古栎(*Quercus mongolica*)等树种的光合及抗性生理进行了研究^[24-27]。然而,对于亚热带地区广布常绿树种的 O_3 敏感性研究较少,结合考虑该地区高水平的 N 沉降以及独特的水热等气候条件,认为该区

树种在 O_3 胁迫响应机制上具有独特性。本试验以我国亚热带典型常绿树种香樟为研究对象,在人工模拟 N 沉降条件下,测定叶绿素、类胡萝卜素、抗坏血酸含量及总抗氧化能力等,分析 O_3 浓度升高对香樟光合色素、抗性生理等的影响,旨在揭示、预测我国长江三角洲地区高水平 N 沉降条件下香樟树种的 O_3 胁迫现状和未来趋势,为科学保护该区这一重要树种提供参考。

1 材料与方法

1.1 试验地点

试验区位于浙江省宁波市天童森林生态系统国家野外科学观测研究站($29^{\circ}48'N, 121^{\circ}47'E$),属典型亚热带季风气候,四季分明,冬季寒冷干燥,夏季温暖湿润。年平均气温 $16^{\circ}C$,最暖月 7 月平均气温 $28.1^{\circ}C$,最冷月 1 月份平均气温 $4.2^{\circ}C$ 。年平均降水为 1375 mm,且主要集中在 6—8 月份。土壤类型为山地红黄壤,土质偏酸,pH 值大约在 4.4—5.1 之间,母质基底为中生代沉积物及入侵性的石英岩和花岗岩。2009 年试验期间(5 月 15 日—9 月 10 日),小时平均气温、空气相对湿度分别为 $16^{\circ}C$ 和 88%,日均太阳辐射量为 $13.8 MJ \cdot m^{-2} \cdot d^{-1}$,8h 平均(9:00—17:00) O_3 浓度为 $32.6 nmol/mol$,小时最高浓度为 $156.3 nmol/mol$ 。

1.2 试验处理

试验材料为 1 年生香樟幼苗,由浙江省嘉兴市桐乡特种苗繁育中心购得,于 2009 年 1 月植入容量为 5 L (高 15 cm×直径 28 cm)的塑料花盆中,栽培基质为当地红黄壤与树皮腐殖质的混合物(体积比 1:1)。盆栽幼苗培育于控温温室,并于 2009 年 4 月中旬移到外界大气环境中进行处理前适应。2009 年 5 月 10 日,选取长势一致的幼苗 90 株(15×6)移植于 6 个开顶气室(OTC,底面为边长 1 m 的正八边形,高 2.4 m,塑钢架构,透光率为 98.3%的高透性塑料膜)中。每个 OTC 中 15 株幼苗分为 3 组,分别设空白对照(N0)、施 $N30 kg \cdot hm^{-2} \cdot a^{-1}$ (N30)、施 $N60 kg \cdot hm^{-2} \cdot a^{-1}$ (N60)。N 施加分 6 次进行(5 月 28 日、6 月 23 日、7 月 7 日、7 月 23 日、8 月 11 日、8 月 27 日),以硝酸铵(NH_4NO_3)溶液形式浇灌于盆内土壤表层,空白对照浇以等量自来水。 O_3 处理从 2009 年 5 月 15 日开始,持续到 2009 年 9 月 10 日,阴雨天停止熏气, O_3 处理设大气 O_3 (AA),大气 $O_3+60 nmol/mol$ (AA+60),大气 $O_3+120 nmol/mol$ (AA+120)3 个水平,每个 O_3 水平设两个 OTC 重复。试验期间,水分浇灌充足,不存在干旱胁迫。

1.3 指标测定

于 2009 年 9 月 6 日选取冠层顶部相同部位成熟叶片(无明显 O_3 伤害症状)打孔($0.9 cm^2$ 叶圆片)取样,叶片在 $4^{\circ}C$ 暗环境下用 4 mL 95% 的乙醇溶液浸泡提取,测定 664、648、470 nm 波长吸光度,根据 Lichtenthaler^[28] 的修正公式计算叶绿素 a、叶绿素 b 以及类胡萝卜素含量。

丙二醛含量采用硫代巴比妥酸法测定^[29]。

抗坏血酸含量参照 Okamura 还原 Fe^{3+} 的方法测定^[30]。

总抗氧化能力的测定采用 FRAP 法^[31],以单位鲜重叶片等效 Fe^{2+} 含量($mmol/g$)表示。

1.4 数据分析

所有测定指标均取 6 次重复,采用 SAS 软件(Version 9.1.3, SAS Institute, Cary, NC, USA)进行分析。运用单变量方差分析模型检验 O_3 、N 以及 O_3 与 N 交互效应的显著性,验后多重比较采取 Tukey 法。如果 O_3 与 N 交互作用不显著,则多重比较分别在两种处理不同水平之间进行;如果 O_3 与 N 交互作用显著,则考察每一施 N 水平下不同 O_3 处理之间的差异显著性。数据均满足分布正态及方差齐性要求, $P \leq 0.05$ 认为差异显著。

2 结果与分析

2.1 O_3 以及 N 处理对香樟幼苗光合色素含量的影响

结果显示:一个生长季 O_3 以及 N 处理显著影响了香樟幼苗叶片光合色素含量,然而,两种处理之间不存在明显的交互作用(表 1)。与 AA 处理比,AA+60 与 AA+120 处理导致叶绿素 a 含量分别下降了 12.7% 和 36.1%,降幅均达到统计显著,且两 O_3 处理之间差异显著。相比于 N0 处理,N30 及 N60 处理均显著提高了叶绿素 a 含量,提高幅度分别为 5.3% 和 80.0%,且两个 N 处理水平之间差异显著。N 处理下叶绿素 b 与叶绿

素 a 具有相同的变化趋势,AA+120 处理显著降低了叶绿素 b 含量,与 AA 处理相比,降幅达 30.9%。相比于 AA 处理及 N0 处理,AA+120 与 N60 处理均显著降低了叶绿素 a 与叶绿素 b 的比值(叶绿素 a/b),对应的下降幅度分别为 6.9% 与 6.4%;AA+60 与 N30 处理导致叶绿素 a/b 较 AA 与 N0 分别下降了 3.9% 和 4.7%,未达到统计显著。叶片类胡萝卜素含量对于 O₃ 与 N 处理的响应类似于叶绿素 a,两种处理效应方向相反,且每种处理两个水平与对照(AA\N0)相比、两个处理水平之间相比均有显著差异(图 1)。

表 1 臭氧(O₃)、氮(N)以及 O₃×N 对各观测指标影响显著性

Table 1 Significance of the effects of ozone(O₃), nitrogen(N) and O₃×N on the examined physiological parameters

测定指标 Physiological parameters	臭氧 O ₃	氮 N	臭氧×氮 O ₃ ×N
叶绿素 a Chlorophyll a/(μg/cm ²)	0.000 **	0.000 **	0.292
叶绿素 b Chlorophyll b/(μg/cm ²)	0.000 **	0.000 **	0.295
叶绿素 a/b Chlorophyll a/b	0.006 **	0.007 **	0.271
类胡萝卜素 Carotenoid/(μg/cm ²)	0.000 **	0.000 **	0.623
丙二醛 MDA/(nmol/g)	0.033 *	0.398	0.099
还原型抗坏血酸 ASC/(μmol/g)	0.008 **	0.262	0.000 **
总抗坏血酸 [ASC+DHA]/(μmol/g)	0.499	0.498	0.016 *
总抗氧化能力 FRAP/(mmol/g)	0.004 **	0.870	0.819

* P<0.05, ** P<0.01

2.2 O₃以及 N 处理对香樟幼苗膜脂过氧化的影响

与 AA 处理相比,AA+120 处理导致香樟幼苗叶片膜质过氧化程度显著加剧,膜脂过氧化产物丙二醛含量升高了 16.1%;然而,AA+60 处理未能显著影响这一过程。N 处理未显著改变香樟叶片膜脂过氧化,O₃ 与 N 处理之间不存在交互作用(图 2、表 1)

2.3 O₃以及 N 处理对香樟幼苗总抗氧化能力的影响

相比于 AA 处理,AA+120 处理导致香樟幼苗叶片总抗氧化能力显著上升,上升幅度为 19.0%;AA+60 处理下,叶片总抗氧化能力较对照提高了 5.8%,未达到统计显著。AA+60 与 AA+120 处理之间叶片总抗氧化能力差异不显著。N 处理未能显著影响香樟叶片的总抗氧化能力,O₃ 与 N 处理之间交互作用不显著(图 2、表 1)。

2.4 O₃以及 N 处理对香樟幼苗抗坏血酸含量及组成的影响

不同施 N 水平下,O₃处理对香樟幼苗叶片抗坏血酸含量及组成的影响存在差异,O₃ 与 N 处理之间交互作用显著(表 1)。N0 下,O₃处理(AA+60 与 AA+120)导致叶片总抗坏血酸含量趋于降低;N30 及 N60 下,O₃处理(AA+60 与 AA+120)导致叶片总抗坏血酸含量趋于上升。然而,这些变化趋势均未达到统计显著(图 3)。

还原型抗坏血酸含量在不同 N 水平下受 O₃影响变化趋势与总抗坏血酸含量变化相似。N0 下,AA+60 与 AA+120 处理对还原型抗坏血酸含量的降低效应均达到显著水平,与 AA 处理相比,降幅分别为 22.5% 和 20.7%;N 施加条件下,相比于 AA 处理,AA+120 处理显著提高了香樟幼苗叶片还原型抗坏血酸含量,N30 处理下提高了 33.4%,N60 处理下提高了 41.3%;AA+60 处理也有类似效应,但未达到显著水平(图 3)。

3 讨论

膜质过氧化被认为是 O₃胁迫条件下植物氧化伤害的重要表征^[32],丙二醛(MDA)作为膜质过氧化的主要产物之一,广泛用于膜脂过氧化和组织伤害程度的诊断^[33]。试验结果表明:AA+120 处理导致香樟幼苗叶片膜质过氧化程度显著加剧(图 2)。O₃胁迫导致的树木叶片膜质过氧化已经在自然生境下的欧洲山毛榉(*Fagus sylvatica*)和欧洲云杉(*Picea abies*)中得到验证^[34-35]。然而,本试验中 AA+60 处理并未显著影响香樟叶片膜脂过氧化,说明香樟作为常绿树种具有一定程度的 O₃胁迫抗性^[17]。王效科等^[36]研究发现:香樟可以 ≥20 μg·g⁻¹(干重)·h⁻¹的速率释放异戊二烯。该化合物可与 O₃发生反应,稀释叶片边界层 O₃浓度,减少气

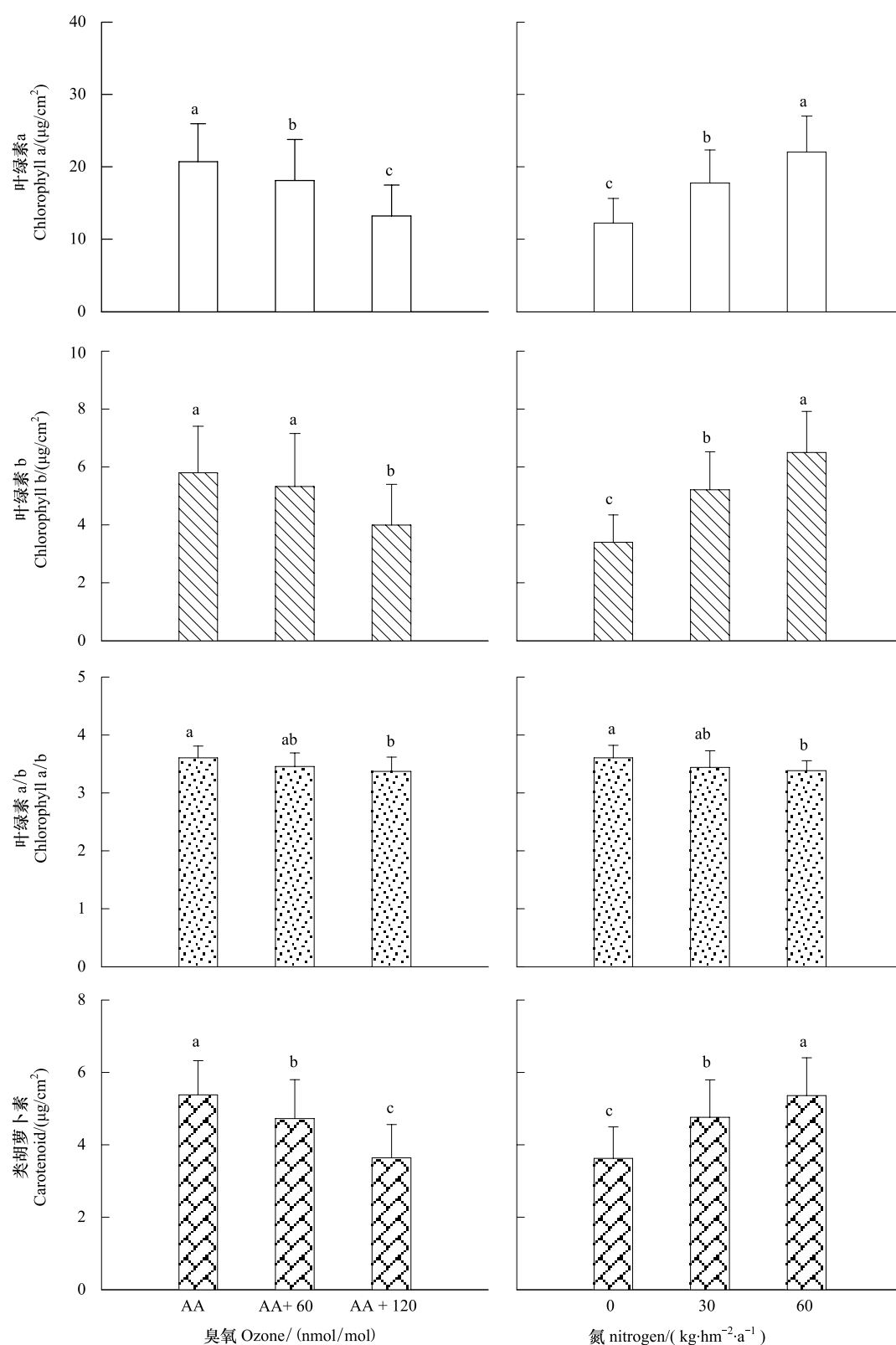


图1 不同臭氧(O_3)与氮(N)处理水平下香樟叶片叶绿素a, 叶绿素b, 叶绿素a/b, 类胡萝卜素含量多重比较, 小写字母a、b、c表示差异显著($P < 0.05$)

Fig. 1 Multiple comparisons for the foliar chlorophyll a, chlorophyll b, chlorophyll a/b and carotenoid content among different ozone(O_3) and nitrogen(N) treatment levels. Lowercase letters a, b and c indicate significant differences ($P < 0.05$)

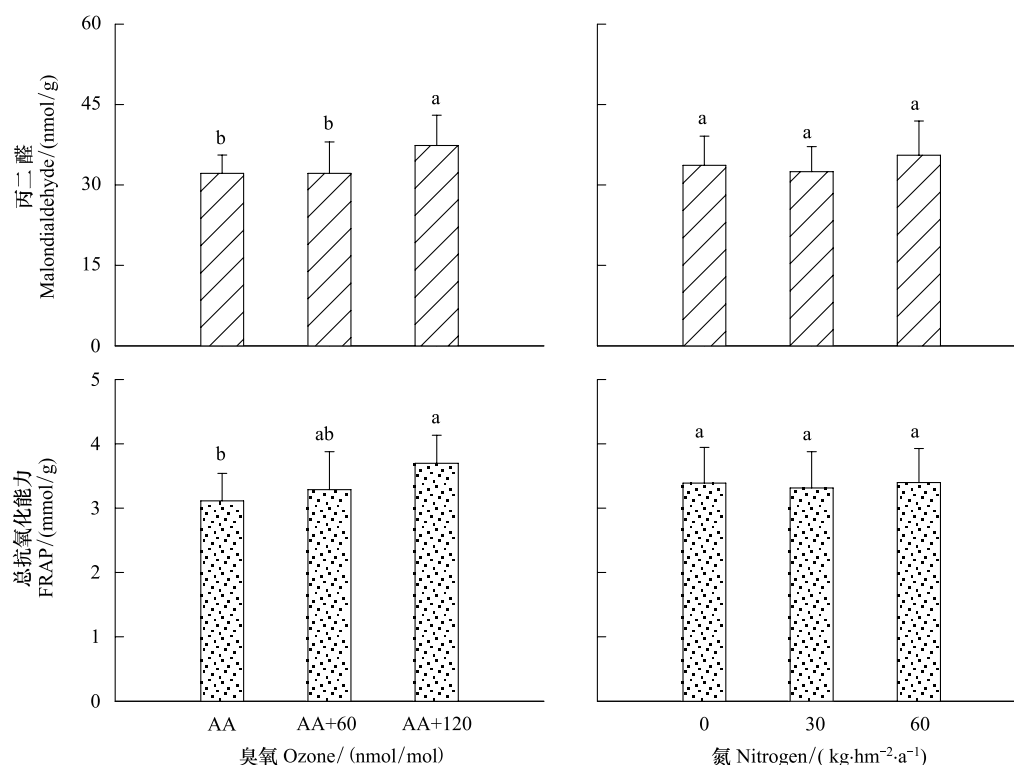


图2 不同臭氧(O₃)与氮(N)处理水平下香樟叶片丙二醛含量及总抗氧化能力多重比较,小写字母a、b、c表示差异显著(P<0.05)

Fig. 2 Multiple comparisons for the foliar MDA content and the FRAP capacity among different ozone (O₃) and nitrogen (N) treatment levels. MDA-Malondialdehyde, FRAP-total antioxidant capacity expressed as $\mu\text{mol Fe}^{2+} \cdot \text{g}^{-1}$ fresh matter. Lowercase letters a, b and c indicate significant differences (P<0.05)

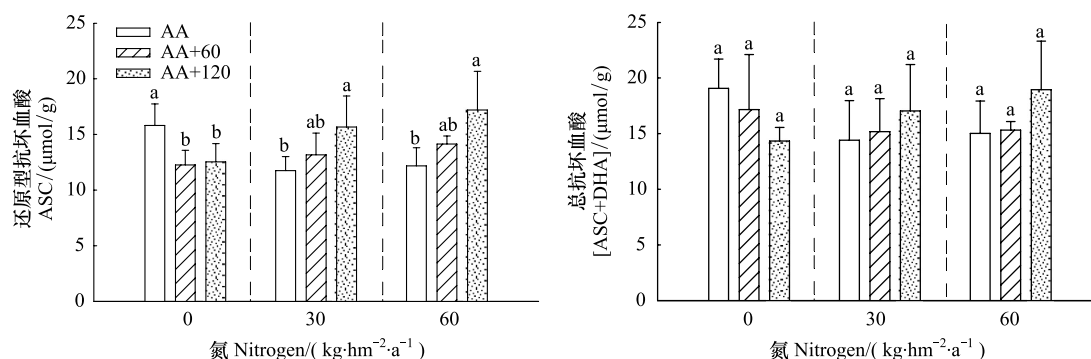


图3 不同施氮(N)水平下臭氧(O₃)胁迫对香樟叶片还原型抗坏血酸(ASC)及总抗坏血酸([ASC+DHA])含量的影响,AA-大气O₃,AA+60-大气O₃+60 nmol/mol;AA+120-大气O₃+120 nmol/mol,不同字母表示差异显著(P<0.05)

Fig. 3 Effect of elevated ozone (O₃) on the foliar content of ASC and [ASC+DHA] in *Cinnamomum Camphora* seedlings under different nitrogen (N) loads. AA-ambient air, AA+60-ambient air plus 60 nmol/mol, AA+120-ambient air plus 120 nmol/mol. Different letters indicate significant differences (P<0.05)

孔 O₃ 通量,进而降低植物 O₃ 胁迫^[37]。N 施加能够提高叶片光合色素特别是叶绿素 a 含量,增强光捕获能力,光能过量捕获可进一步导致过氧离子产生,进而对植物膜脂过氧化具有潜在加剧效应^[38]。然而,本研究中 N 施加未显著影响香樟叶片膜脂过氧化,N 施加在刺激植物光能捕获的同时,显著促进了香樟叶片光合作用光化学反应过程^[21],光化学反应对捕获光能的消耗在一定程度上缓解了后者的氧化胁迫效应(图2)。Zhao 等研究发现:环境温度下,N 素施加 (250 kg·hm⁻²·a⁻¹) 显著降低了粗枝云杉 (*Picea asperata*) 幼苗叶片 MDA 含

量;而在红外加热条件下,施 N 导致叶片膜脂过氧化显著加剧^[39]。N 施加对树木叶片膜脂过氧化的影响可能与植物生长环境密切相关。

植物体内的抗氧化系统是植物 O₃ 抗性的基础,能够清除胁迫产生的活性氧及膜脂过氧化的有毒产物,有利于植物的逆境生存^[14]。抗坏血酸作为植物体内最重要的抗氧化剂,其含量与植物 O₃ 抗性显著正相关^[40]。本试验中,O₃ 胁迫导致的香樟叶片抗坏血酸含量变化与 N 素施加有关:N30 及 N60 处理下,O₃ 胁迫促使叶片抗坏血酸含量上升,以还原型抗坏血酸含量上升为主,且在 AA+120 处理下效应达到显著;N0 条件下,O₃ 胁迫导致叶片总抗坏血酸及还原型抗坏血酸含量均有所下降,且以还原型抗坏血酸含量下降为主,达到统计显著(图 3)。该结果一方面论证了还原型抗坏血酸在植物体活性氧清除过程中的重要作用^[41];另一方面说明试验中 N 素的施加能够为 O₃ 胁迫下植物体抗坏血含量的提高提供必要营养支持^[42]。N 施加对树木氧化抗性的增强效应在常绿硬叶树种冬青栎、针叶树种冷杉中也有报道^[18-19]。此外,本试验中 AA+120 处理导致香樟叶片总抗氧化能力显著升高(图 2),这可能与抗坏血酸含量的升高有关^[43],也可能是胞质中其他类型抗氧化物质如谷胱甘肽(Glutathione)^[4]等的含量上升导致。

植物体叶绿素含量降低是 O₃ 胁迫最普遍的效应之一^[44-45]。本实验中 O₃ 处理(AA+60 以及 AA+120)显著降低了香樟幼苗叶片叶绿素 a 及类胡萝卜素含量(图 1),叶绿素 b 含量在 AA+120 处理下也呈显著下降(图 1)。叶绿素的降解与叶绿体膜的脂质过氧化有关^[46],并与核酮糖 1,5-二磷酸羧化酶(Rubisco)的降解过程相偶联^[47]。膜脂过氧化可引起膜通透性改变,活性氧分子通过膜通道或以渗透方式进入叶绿体内,直接作用于叶绿素分子,或通过进攻 Rubisco 活性位点间接介导叶绿素的降解。此外,本试验结果显示:AA+120 与 N60 处理均显著降低了香樟叶片叶绿素 a 与叶绿素 b 含量的比值(图 1),叶绿素 a/b 值的下降意味着叶片的加速衰老^[48]。另一方面,与 O₃ 胁迫效应相反,本试验中 N 施加显著提高了香樟叶片叶绿素 a、叶绿素 b、及类胡萝卜素的含量,然而,施 N 未能有效阻止 O₃ 胁迫导致的叶绿素降解,两种处理之间不存在显著交互作用。这一结论与 Watanabe 等针对 2 年生短柄枹栎(*Quercus serrata*) 幼苗的研究结论一致^[49]; Utriainen 和 Holopainen^[50]研究了施 N 条件下欧洲赤松(*Pinus sylvestris*) 幼苗的 O₃ 胁迫效应,结果显示:N 施加显著提高了叶片叶绿素及类胡萝卜素含量,然而,N 施加对光合色素的促进效应与 O₃ 抑制效应之间同样不存在显著交互作用。O₃ 与 N 处理对植物光合色素的影响可能受植物体内不同生理机制独立调控。

4 结论

(1) AA+60 处理未对香樟叶片膜脂过氧化产生显著影响,香樟较落叶、针叶树种具有较强的 O₃ 抗性,这可能与其释放的挥发性异戊二烯能够与 O₃ 反应,对叶片边界层 O₃ 具有稀释作用有关;施 N 条件下,AA+120 处理导致香樟叶片还原型抗坏血酸含量显著升高,N 施加可为 O₃ 胁迫下抗氧化物的合成提供必要营养支持;AA+120 处理导致香樟叶片衰老加速,光合色素含量降低,这可能与叶绿体膜脂质过氧化及核酮糖 1,5-二磷酸羧化酶的降解有关;N 施加显著增加了香樟叶片光合色素含量,然而施 N 未能有效缓解 O₃ 胁迫导致的膜脂过氧化和叶绿素降解。

(2) 控制实验条件下充足的水分供给、盆栽对植物根系生长限制以及树木幼苗阶段生长发育的独特生理生长机制等因素可能导致本试验所得结果存在一定偏差,研究结论在推广到自然生境下成熟树木的时候还需结合原位观测进行相关校正。考虑到亚热带地区独特的气候、地理和植被条件,在全球变化的大背景下加强该区树种 O₃ 胁迫敏感性研究十分必要。

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References:

- [1] Ashmore M R. Assessing the future global impacts of ozone on vegetation. *Plant, Cell and Environment*, 2005, 28(8): 949-964.
- [2] Solomon S, Qin D, Manning M, Chen Z, Murquis M, Averyt K B, Tignor M, Miller H L. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2007.

- [3] Society R, Fowler D. Ground-Level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications; Science Policy Report 15/08. London; Royal Society, 2008.
- [4] Wilkinson S, Mills G, Illidge R, Davies W J. How is ozone pollution reducing our food supply?. *Journal of Experimental Botany*, 2011, 10: 1-10.
- [5] Yamaji K, Akimoto H. Future prediction of surface ozone over East Asia up to 2020. Report of the 6th Annual CMAS conference, Chapel Hill, NC, 2007.
- [6] Xu X, Lin W, Wang T, Yan P, Tang J, Meng Z, Wang Y. Long-term trend of surface ozone at a regional background station in eastern China 1991—2006: enhanced variability. *Atmospheric Chemistry and Physics*, 2008, 8(1): 215-243.
- [7] Kohno Y, Matsumura H, Ishii T, Izuta T. Establishing critical levels of air pollutants for protecting East Asian vegetation—a challenge. *Plant Responses to Air Pollution and Global Change*, 2005, VII: 243-250.
- [8] Fisher L S, Mays P A, Wylie C L. An overview of nitrogen critical loads for policy makers, stakeholders, and industries in the United States. *Water, Air and Soil Pollution*, 2007, 179(1/4): 3-18.
- [9] Liu X J, Duan L, Mo J M, Du E Z, Shen J L, Lu X K, Zhang Y, Zhou X B, He C N, Zhang F S. Nitrogen deposition and its ecological impact in China: an overview. *Environmental Pollution*, 2011, 159(10): 2251-2264.
- [10] Maskell L C, Smart S M, Bullock J M, Thompson K, Stevens C J. Nitrogen deposition causes widespread loss of species richness in British habitats. *Global Change Biology*, 2010, 16(2): 671-679.
- [11] Grulke N E. Plasticity in physiological traits in conifers: implications for response to climate change in the western US. *Environmental Pollution*, 2010, 158(6): 2032-2042.
- [12] Long S P, Naidu S L. Effects of oxidants at the biochemical, cell and physiological levels, with particular reference to ozone//Bell J N B, Treshow M, eds. *Air Pollution and Plant Life*. West Sussex; New York; John Wiley & Sons, 2002: 69-88.
- [13] Fiscus E L, Booker F L, Burkey K O. Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning. *Plant, Cell and Environment*, 2005, 28(8): 997-1011.
- [14] Wang J L, Wang Y, Zhao T H, Cao Y, Liu Y L, Duan M. Effects of ozone on AsA-GSH cycle in soybean leaves. *Acta Ecologica Sinica*, 2011, 31(8): 2068-2075.
- [15] Zheng Y F, Hu C D, Wu R J, Zhao Z, Liu H J, Shi C H. Experiment with effects of increased surface ozone concentration upon winter wheat photosynthesis. *Acta Ecologica Sinica*, 2010, 30(4): 847-855.
- [16] Conklin P L, Barth C. Ascorbic acid, a familiar small molecule intertwined in the response of plants to ozone, pathogens, and the onset of senescence. *Plant, Cell and Environment*, 2004, 27: 959-970.
- [17] Niu J F, Zhang W W, Feng Z Z, Wang X K, Tian Y. Impact of elevated O₃ on visible foliar symptom, growth and biomass of *Cinnamomum camphora* seedlings under different nitrogen loads. *Journal of Environmental Monitoring*, 2011, 13(10): 2873-2879.
- [18] Guo J Y, Yang Y, Wang G X, Yang L D, Sun X Y. Ecophysiological responses of *Abies fabri* seedlings to drought stress and nitrogen supply. *Physiologia Plantarum*, 2010, 139(4): 335-347.
- [19] Andivia E, Márquez-García B, Vázquez-Piqué j, Córdoba F, Fernández M. Autumn fertilization with nitrogen improves nutritional status, cold hardiness and the oxidative stress response of Holm oak (*Quercus ilex* ssp. *ballota* [Desf.] Samp) nursery seedlings. *Trees*, 2012, 26(2): 311-320.
- [20] Calatayud A, Pomares F, Barreno E. Interactions between nitrogen fertilization and ozone in watermelon cultivar Reina de Corazones in open-top chambers. Effects on chlorophyll a fluorescence, lipid peroxidation, and yield. *Photosynthetica*, 2006, 44(1): 93-101.
- [21] Feng Z Z, Niu J F, Zhang W W, Wang X K, Yao F F, Tian Y. Effects of ozone exposure on sub-tropical evergreen *Cinnamomum camphora* seedlings grown in different nitrogen loads. *Trees*, 2011, 25(4): 617-625.
- [22] Wittig V E, Ainsworth E A, Naidu S L, Karnosky D F, Long S P. Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis. *Global Change Biology*, 2009, 15(2): 396-424.
- [23] Nali C, Paoletti E, Marabottini R, Rocca G D, Lorenzini G, Paolacci A R, Ciaffi M, Badiani M. Ecophysiological and biochemical strategies of response to ozone in Mediterranean evergreen broadleaf species. *Atmospheric Environment*, 2004, 38(15): 2247-2257.
- [24] He X Y, Fu S L, Chen W, Zhao T H, Xu S, Tuba Z. Changes in effects of ozone exposure on growth, photosynthesis, and respiration of *Ginkgo biloba* in Shenyang urban area. *Photosynthetica*, 2007, 45(4): 555-561.
- [25] Zhang W W, Zhao T H, Wang M Y, He X Y, Fu S L. Effects of elevated ozone concentration on *Ginkgo biloba* photosynthesis. *Chinese Journal of Ecology*, 2007, 26(5): 645-649.
- [26] Ruan Y N, He X Y, Chen W, Chen Z J, Sun Y. Effects of elevated O₃ concentration on anti-oxidative enzyme activities in *Pinus tabulaeformis*. *Chinese Journal of Applied Ecology*, 2009, 20(5): 1032-1037.
- [27] Yan K, Chen W, He X Y, Zhang G Y, Xu S, Wang L L. Responses of photosynthesis, lipid peroxidation and antioxidant system in leaves of *Quercus mongolica* to elevated O₃. *Environmental and Experimental Botany*, 2010, 69(2): 198-204.
- [28] Lichtenthaler H K. Chlorophylls and carotenoids, pigments of photosynthetic biomembranes. *Methods in Enzymology*, 1987, 148: 350-382.

- [29] Heath R L, Packer L. Photoperoxidation in isolated chloroplasts: I. Kinetics and stoichiometry of fatty acid peroxidation. *Archives of Biochemistry and Biophysics*, 1968, 125(1): 189-198.
- [30] Masato O. An improved method for determination of L-ascorbic acid and L-dehydroascorbic acid in blood plasma. *Clinica Chimica Acta*, 1980, 103(3): 259-268.
- [31] Griffin S P, Bhagooli R. Measuring antioxidant potential in corals using the FRAP assay. *Journal of Experimental Marine Biology and Ecology*, 2004, 302(2): 201-211.
- [32] Brunschön-Harti S, Fangmeier A, Jäger H J. Influence of ozone and ethylenediurea (EDU) on growth and yield of bean (*Phaseolus vulgaris* L.) in open-top field chambers. *Environmental Pollution*, 1995, 90(1): 89-94.
- [33] Shulaev V, Oliver D J. Metabolic and proteomic markers for oxidative stress. New tools for reactive oxygen species research. *Plant Physiology*, 2006, 141(2): 367-372.
- [34] Srámek V, Novotný R, Bednářová E, Uhlířová H. Monitoring of ozone risk for forest in the Czech Republic: preliminary results. *The Scientific World Journal*, 2007, 7(S1): 78-83.
- [35] Hãnová I, Novotný R, Uhlířová H, Vráblík T, Horálek J, Lomský B, Šrámek V. The impact of ambient ozone on mountain spruce forests in the Czech Republics indicated by malondialdehyde. *Environmental Pollution*, 2010, 158(7): 2393-2401.
- [36] Wang X K, Mu Y J, Ouyang Z Y, Zhan X S, Ni S F, Fu C X. Study on emission of isoprene from major plants living in Taihu basin. *Chinese Bulletin of Botany*, 2002, 19(2): 224-230.
- [37] Fares S, Goldstein A, Loreto F. Determinants of ozone fluxes and metrics for ozone risk assessment in plants. *Journal of Experimental Botany*, 2009, 61(3): 629-633.
- [38] Holste E K, Kobe R K, Vriesendorp C F. Seedling growth responses to soil resources in the understory of a wet tropical forest. *Ecology*, 2011, 92(9): 1828-1838.
- [39] Zhao C Z, Liu Q. Growth and physiological responses of *Picea asperata* seedlings to elevated temperature and to nitrogen fertilization. *Acta Physiologiae Plantarum*, 2009, 31(1): 163-173.
- [40] Smirnoff N. Ascorbic acid: metabolism and functions of a multifaceted molecule. *Current Opinion in Plant Biology*, 2000, 3(3): 229-235.
- [41] Chen Z, Gallie D R. Increasing tolerance to ozone by elevating foliar ascorbic acid confers greater protection against ozone than increasing avoidance. *Plant Physiology*, 2005, 138(3): 1673-1689.
- [42] Kansal B D, Singh B, Bajaj K L, Kaur G. Effect of different levels of nitrogen and farmyard manure on yield and quality of spinach (*Spinacea oleracea* L.). *Plant Foods for Human Nutrition (Formerly Qualitas Plantarum)*, 1981, 31(2): 163-170.
- [43] Severino J F, Stich K, Soja G. Ozone stress and antioxidant substances in *Trifolium repens* and *Centaurea jacea* leaves. *Environmental Pollution*, 2007, 146(3): 707-714.
- [44] Broadmeadow M S J, Jackson S. Growth responses of *Quercus petraea*, *Fraxinus excelsior* and *Pinus sylvestris* to elevated carbon dioxide, ozone and water supply. *New Phytologist*, 2000, 146(3): 437-451.
- [45] Manninen S, Le Thiec D, Rose C, Nourrisson G, Radnai F, Garrec J P, Huttunen S. Pigment concentrations and ratios of Aleppo pine seedlings exposed to ozone. *Water, Air, and Soil Pollution*, 1999, 116(1/2): 333-338.
- [46] Dhindsa R S, Plumb-Dhinds P, Thorpe T A. Leaf senescence: correlated with increased levels of membrane permeability and lipid peroxidation, and decreased levels of superoxide dismutase and catalase. *Journal of Experimental Botany*, 1981, 32(1): 93-101.
- [47] Feller U, Anders I, Mae T. Rubiscolytics: fate of Rubisco after its enzymatic function in a cell is terminated. *Journal of Experimental Botany*, 2008, 59(7): 1615-1624.
- [48] Schelbert S, Aubry S, Burla B, Agne B, Kessler F, Krupinska K, Hörtensteiner S. Pheophytin pheophorbide hydrolase (Pheophytinase) is involved in chlorophyll breakdown during leaf senescence in Arabidopsis. *The Plant Cell*, 2009, 21(3): 767-785.
- [49] Watanabe M, Yamaguchi M, Tabe C, Iwasaki M, Yamashita R, Funada R, Fukami M, Matsumura F, Kohno Y, Izuta T. Influences of nitrogen load on the growth and photosynthetic responses of *Quercus serrata* seedlings to O₃. *Trees*, 2007, 21(4): 421-432.
- [50] Utriainen J, Holopainen T. Nitrogen availability modifies the ozone responses of Scots pine seedlings exposed in an open-field system. *Tree Physiology*, 2001, 21(16): 1205-1213.

参考文献:

- [14] 王俊力, 王岩, 赵天宏, 曹莹, 刘玉莲, 段萌. 臭氧胁迫对大豆叶片抗坏血酸-谷胱甘肽循环的影响. *生态学报*, 2011, 31(8): 2068-2075.
- [15] 郑有飞, 胡程达, 吴荣军, 赵泽, 刘宏举. 石春红. 地表臭氧浓度增加对冬小麦光合作用的影响. *生态学报*, 2010, 30(4): 847-855.
- [25] 张巍巍, 赵天宏, 王美玉, 何兴元, 付士磊. 臭氧浓度升高对银杏光合作用的影响. *生态学杂志*, 2007, 26(5): 645-649.
- [26] 阮亚男, 何兴元, 陈玮, 陈振举, 孙雨. 臭氧浓度升高对油松抗氧化系统活性的影响. *应用生态学报*, 2009, 20(5): 1032-1037.
- [36] 王效科, 牟玉静, 欧阳志云, 张晓山, 倪士峰, 傅承. 太湖流域主要植物异戊二烯排放研究. *植物学通报*, 2002, 19(2): 224-230.

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