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干扰强度对亚热带米槠人促更新林土壤呼吸及其组分的影响

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摘 要 研究轻度干扰和重度干扰对亚热带米槠人促更新林土壤总呼吸、异养呼吸的影响. 结果表明:与轻度干扰米槠林相比,重度干扰林的土壤呼吸及其各组分均下降,其中,自养呼吸(R_A,1.75 t C · hm^{-2} · a^{-1})下降了 40%.与轻度干扰林相比,重度干扰林土壤有机碳储量、细根生物量和凋落物量均显著降低.土壤温度可以分别解释轻度干扰林土壤呼吸(R_S)、异养呼吸(R_H)、自养呼吸(R_A)的 84.7%、68.3%、5.1%,可以解释重度干扰林的 84.4%、54.6%、21.7%.轻度干扰林和重度干扰林 R_S、R_H、R_A的 Q_{10}值分别为 1.75、1.93、1.27 和 2.46、2.34、1.65. 随着干扰强度的增加,森林生态系统碳储量降低,土壤呼吸下降,且土壤呼吸及其各组分对外界环境变化的响应更明显,生态系统表现出脆弱性,重度干扰下森林生态系统在短时间内难以恢复.

关键词 干扰强度; 人促更新; 土壤呼吸; 土壤温度; 土壤含水量

Effects of interference intensity on soil respiration and its components in *Castanopsis carlesii* forest with artificially assisted regeneration in subtropical China. CHEN Zhong[1,2,3], LIN Cheng-fang[1,2,3], ZHANG Xing-xing[1,2,3], LIN Wei-sheng[1,2,3*], LIU Xiao-fei[1,2,3], LI Yi-qing[1,2,3,4], YANG Yu-sheng[1,2,3] ([1]*School of Geographical Science, Fujian Normal University, Fuzhou* 350007, *China*; [2]*Cultivation Base, State Key Laboratory of Humid Subtropical Mountain Ecology, Fuzhou* 350007, *China*; [3]*Sanming Research Station of Forest Ecosystem and Global Change, Sanming* 365000, *Fujian, China*; [4]*College of Agriculture, Forestry and Natural Resource Management, University of Hawaii, Hilo, HI* 96720, *USA*).

Abstract: The effects of interference intensity on soil respiration (R_S) and heterotrophic respiration (R_H) were studied in two *Castanopsis carlesii* forests with artificially assisted regeneration. The results showed that *C. carlesii* forest decreased the R_S and its components with the increasing interference intensity, particularly decreased its autotrophic respiration (R_A, 1.75 t C · hm^{-2} · a^{-1}) by 40% under high interference than under low interference. Compared with *C. carlesii* forest under low interference, soil organic carbon, fine root biomass, and annual litterfall biomass of *C. carlesii* forest were significantly reduced under high interference. Soil temperature could explain the seasonal variations of R_S, R_H, and R_A with 84.7%, 68.3% and 5.1% for the *C. carlesii* forest under low interference, and with 84.4%, 54.6% and 21.7% for the *C. carlesii* forest under high interference, respectively. The Q_{10} values of R_S, R_H and R_A in the *C. carlesii* forest were 1.75, 1.93, 1.27 under low interference, and 2.46, 2.34, 1.65 under high interference, respectively. Carbon storage and soil respiration of forest ecosystem would decrease with the increasing interference intensity, the responses of soil respiration and its components to environmental change were obvious, and forest ecosystem showed vulnerability. It indicated the difficulty of restoring forest ecosystem with high interference

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during a short term.

Key words: interference intensity; artificially assisted regeneration; soil respiration; soil temperature; soil water content.

土壤呼吸(R_S)是土壤碳排放的主要形式[1],每年向大气的排放量可达 86~110 Pg C[2],相当于化石燃料燃烧碳排放量的 10 多倍[3].因此,土壤呼吸微小的变动都会显著改变大气 CO_2浓度.土壤呼吸包括自养呼吸(R_A,由根系及根系微生物呼吸组成)和异养呼吸(R_H,主要由土壤微生物呼吸组成)[4].不同组分土壤呼吸值的变化很大程度受控于外界环境因子的变化(如土壤温度、含水量等)[5-6],且不同组分对环境因子变化的响应差异明显.因此,区分土壤呼吸的组分是研究生态系统碳排放及评估土壤碳收支的重要环节.

常绿阔叶林人工促进天然更新(简称人促更新)是天然用材林更新的重要方法,在二十世纪七八十年代被广泛推广.人促更新在经营过程中的一个重要措施是在林分生长过程中定期劈除生长较差的非目的树种和杂灌,根据劈除非目的树种强度和频率又将人促更新分成重度干扰人促更新和轻度干扰人促更新.而不同干扰强度对人促更新林的生物量、生产力、群落组成有显著影响[7-9].有研究表明,不同研究区域自养呼吸对总呼吸的贡献存在差异(贡献值为 45%~50%),并认为不同研究区域植被组成的差异(主要是树种、群落多样性、生物量等)是其原因之一[10-11].因此,不同干扰强度对人促更新林土壤呼吸及其不同组分的影响可能不同.本文对轻度干扰和重度干扰下亚热带米槠人促更新林土壤呼吸不同组分进行研究,为合理的人促更新经营提供科学依据.

1 研究地区与研究方法

1.1 研究区概况

试验样地位于福建三明森林生态系统和全球变化研究站陈大镇观测点(26°19′ N, 117°36′ E),地处武夷山东南,戴云山西北,以低山丘陵为主,平均海拔 330 m,平均坡度为 30°~40°[12].该地区为中亚热带区域,气候属中亚热带季风气候,年均温 19.1 ℃,年均降水量 1749 mm,且集中于 3—8 月,年均蒸发量 1585 mm,相对湿度 81%.该地土壤为花岗岩发育的红壤,其厚度超过 1 m,轻度干扰和重度干扰 2 种林分的土壤理化性质见表 1.

2 种干扰林分的林龄相近,且有相同的立地条件,在受到人为干扰前均为米槠天然林.其中,轻度干扰林为米槠天然林经强度择伐后,封山育林,经过 40 多年次生演替而形成的天然更新林,其林分密度为 3788 株 · hm^{-2},平均树高 18.5 m,平均胸径 15.5 cm.林内群落层次明显,乔木层主要树种有米槠(*Castanopsis carlesii*)、闽粤栲(*C. fissa*)、黄丹木姜子(*Litsea elongate*)、新木姜子(*Neolitsea aurata*)等;灌木层主要有木荚红豆(*Ormosia xylocarp*)、毛石楠(*Photinia hirsute*)、罗浮栲(*C. abri*)等组成;草本层主要由狗脊蕨(*Woodwardia japonica*)、黑莎草(*Gahnia tristis*)、油草(*Leptochloa chinensis*)等组成.重度干扰林是米槠天然林经过强度择伐后天然更新,并在更新的过程中定期劈除生长较差的非目的树种和杂灌,保留生长迅速的树种而形成的米槠人工促进更新林,其林分密度为 2158 株 · hm^{-2},平均树高 13.7 m,平均胸径 16.8 cm.其乔木层主要树种有米槠、木荷(*Schima superba*)和东南野桐(*Malloyus lianus*)等; 灌木层主要由鼠刺(*Itea chinensis*)、毛叶冬青(*Ilex pubilimba*)和石栎(*Lithocarpus glabe*)等组成;草本层不发达,主要由鳞子莎(*Lepidosperma chinense*)、狗脊蕨、扇叶铁线蕨(*Adiantum flabellulatum*)等组成.

表 1 试验样地土壤理化性质

Table 1 Soil physical and chemical properties at sampling plots

试验地 Sampling plot	土壤深度 Soil depth (cm)	有机碳 Organic carbon (g · kg^{-1})	全 N Total N (g · kg^{-1})	全 P Total P (g · kg^{-1})	容重 Bulk density (g · cm^{-3})	细根生物量 Fine root biomass (kg · m^{-3})	年凋落物量 Annual litterfall biomass (t · hm^{-2})
米槠轻度干扰林	0~10	26.94	1.74	0.15	1.08	1.41	5.81
Castanopsis carlesii forest with low interference	10~20	13.98	1.24	0.14	1.21	0.60	
米槠重度干扰林	0~10	20.90	1.58	0.34	1.16	1.02	5.65
Castanopsis carlesii forest with high interference	10~20	9.39	1.10	0.10	1.26	0.40	

1.2　试验设计

2012 年 6 月,分别于 2 种不同干扰强度的米槠人促更新林内设置 3 块 20 m×20 m 样地,在每块样地内随机埋入 3 个 PVC 材质的土壤呼吸圈(内径 20 cm、高 10 cm)作为对照,测定土壤总呼吸.在 3 个呼吸圈附近挖壕沟,选取 1 m×1 m 的小区,在其周围用铁锹开挖壕沟,垂直下挖 0.6~0.8 m,切断根系但不移除,插入细密的尼龙网(100 目),以阻止根系向小区内生长[4],定期清除壕沟小区中的地表植被.在壕沟内插入 3 个土壤呼吸圈用作异养呼吸速率的测定.

土壤呼吸速率采用 Li-8100 开路式土壤碳通量测量系统(Li-COR, USA)连接短期测量室(20 cm 便携测量室 8100-103)进行测定.于 2014 年 1—12 月,选择每月的 15 日和 30 日对各处理中每个呼吸圈测定一次土壤呼吸,测定时间为 9:00—12:00.采用时域反射仪 TDR(Model TDR300, Specturm company, USA)测定土壤圈周围 0~10 cm 深的土壤含水量.采用长杆电子温度探针(SK-250WP,Sato Keiryoki,Kanda,Japan)测定土壤圈周围 5 cm 深的土壤温度.

1.3　数据处理

采用 Excel 2013 和 SPSS 19.0 软件对数据进行统计分析.采用单因素方差分析(one-way ANOVA)对 2 种不同干扰强度米槠人促更新林土壤呼吸及其组分的差异性进行检验($\alpha=0.05$).利用 Origin 9.0 软件作图.图表中数据为平均值±标准差.

采用线性模型、非线性模型对土壤呼吸速率与土壤温度、土壤含水量的关系进行拟合:

$$R_S=aW+b \quad (1)$$

$$R_S=ae^{bt} \quad (2)$$

$$R_S=ae^{bt}W^c \quad (3)$$

式中:R_S为土壤呼吸速率;t 为土壤 5 cm 深处温度;W 为 0~12 cm 土层土壤含水量;a、b、c 为待定系数.

土壤呼吸的温度敏感性(Q_{10})计算公式:

$$Q_{10}=e^{10b} \quad (4)$$

式中:b 为式(2)中拟合所得的温度反应系数.

按每月月中、月末 2 次测定土壤呼吸,并分别以月中、月末的土壤呼吸速率代表该月上半月和下半月的平均呼吸速率,再通过累加方式计算得到土壤呼吸年通量.

2　结果与分析

2.1　土壤呼吸及组分的季节变化

2 种不同干扰强度米槠人促更新林的土壤呼吸速率(R_S)、异养呼吸速率(R_H)和自养呼吸速率(R_A)均表现出明显的季节变化.如图 1 所示,R_S、R_H均呈明显的单峰曲线,而 R_A分别在春夏两季有明显的峰值.图 2 中,轻度干扰林和重度干扰林 R_S分别为 1.51~5.17 和 0.72~5.01 μmol·m^{-2}·s^{-1},最大值均出现在 8 月下旬,最小值分别出现在 1 月的上旬和下旬.轻度干扰林和重度干扰林 R_S年平均值分别为(3.32±0.26)和(2.86±0.19) μmol·m^{-2}·s^{-1},二者间差异显著.此外,轻度干扰林和重度干扰林 R_A分别为 0.14~1.93 和 0.11~1.3 μmol·m^{-2}·s^{-1},最大值分别出现在 4 月上旬和 5 月上旬,最小值分别出现在 12 月上旬和 2 月上旬;R_A年平均值分别为(0.78±0.06)和(0.47±0.01) μmol·m^{-2}·s^{-1};二者间差异显著.轻度干扰林和重度干扰林 R_H分别为 0.99~4.75和 0.48~4.33 μmol·m^{-2}·s^{-1},最大值分别出现在 9 月上旬和 8 上旬,最小值出现在 3 月上旬和 1 月下旬;R_H年平均值分别为 2.54 和 2.39 μmol·m^{-2}·s^{-1},轻度干扰林大于重度干扰林,但二者间差异不显著.

2.2　土壤呼吸年通量及其组分所占比例

由表 2 可以看出,轻度干扰林 R_S、R_H及 R_A年通量较重度干扰林分别高出 16.3%、6.5%、66.3%.在异养呼吸组分上,重度干扰林的呼吸年通量贡献比例较轻度干扰林高 7%;在自养呼吸组分上,轻度干扰林的呼吸年通量贡献比例更大.

2.3　土壤呼吸及其组分与土壤温度、土壤含水量的关系

由图 3 可以看出,在观测期间,轻度干扰林和重度干扰林 5 cm 深土壤温度均表现出明显的季节变化,2 种林分土壤温度最高值分别出现在 8 月下旬和7月下旬,最低值均出现在2月,两者的年变化范

表 2　土壤呼吸年通量及各组分所占比例

Table 2　Annual carbon fluxes of soil respiration and proportion of components to soil respiration

研究对象 Study object	土壤呼吸及其组分 Soil respiration and component	年通量 Annual carbon flux (t C·hm^{-2}·a^{-1})	各组分所占比例 Proportion of component to soil respiration (%)
米槠轻度干扰林	R_S	12.41±0.97	100
Castanopsis carlesii	R_H	9.50±1.12	76.6
forest with low interference	R_A	2.91±0.21	23.4
米槠重度干扰林	R_S	10.67±0.70	100
Castanopsis carlesii	R_H	8.92±0.76	83.6
forest with high interference	R_A	1.75±0.05	16.4

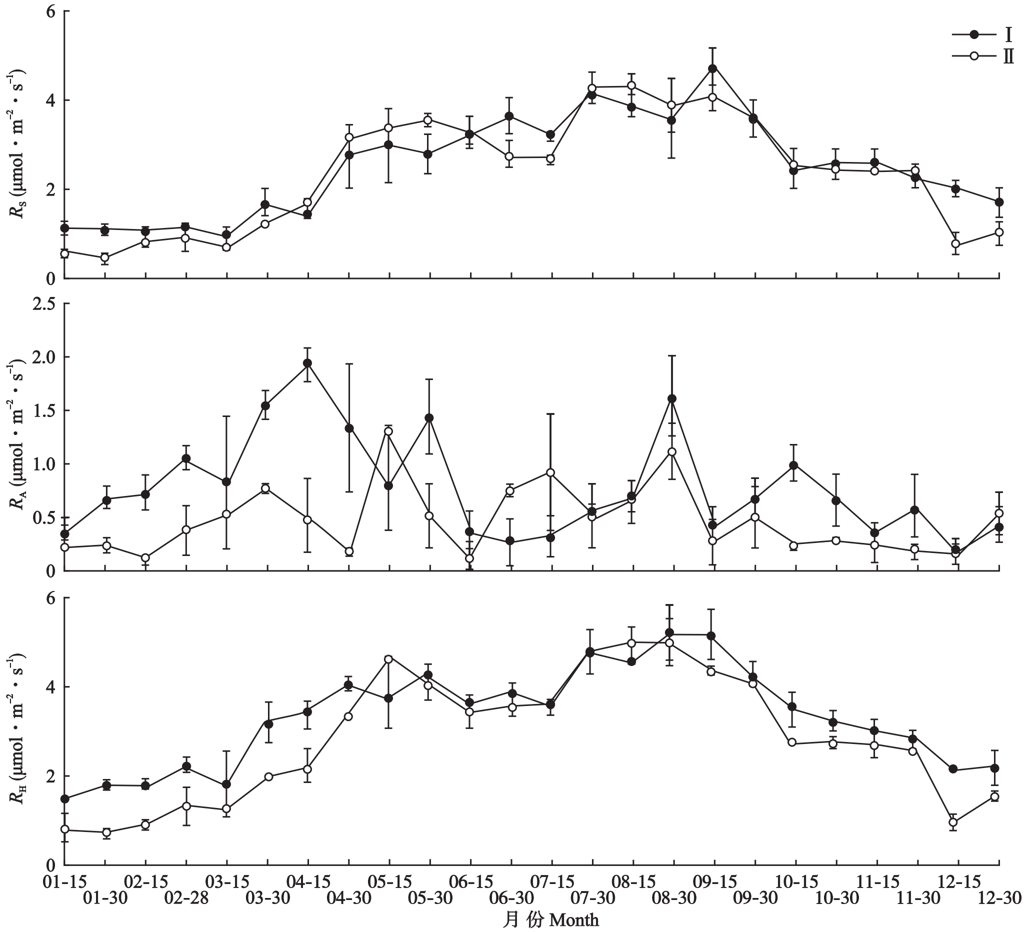

图 1　米槠轻度干扰林和重度干扰林土壤呼吸速率(R_S)、异养呼吸速率(R_H)和自养呼吸速率(R_A)的年动态

Fig.1　Annual dynamics of soil respiration rate (R_S), heterotrophic respiration rate (R_H), and autotrophic respiration rate (R_A) in *Castanopsis carlesii* forests with low interference and high interference.

Ⅰ：米槠轻度干扰林 *C. carlesii* forest with low interference；Ⅱ：米槠重度干扰林 *C. carlesii* forest with high interference. 下同 The same below.

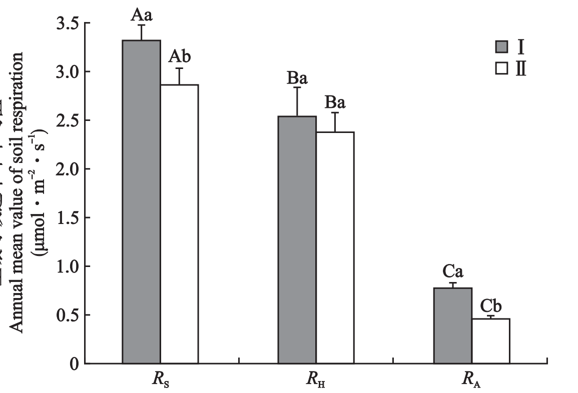

图 2　米槠轻度干扰林和重度干扰林土壤呼吸速率(R_S)、异养呼吸速率(R_H)和自养呼吸速率(R_A)的年平均值

Fig.2　Annual mean of soil respiration rate (R_S), heterotrophic respiration rate (R_H), and autotrophic respiration rate (R_A) in *Castanopsis carlesii* forests with low interference and high interference.

不同大写字母表示同一林分不同组分间差异显著，不同小写字母表示同一组分不同林分间差异显著($P<0.05$) Different capital letters in the same forest meant significant difference among different components, and different small letters in the same component meant significant difference between different forests at 0.05 level.

围分别为 5.83～25.76 ℃和 6.73～27.88 ℃.表 3 显示，除了轻度干扰林的 R_A 外，轻度干扰林及重度干扰林不同组分土壤呼吸均与 5 cm 深处土壤温度呈显著正相关.采用仅考虑温度的非线性模型拟合发现，土壤温度可以分别解释轻度干扰林 R_S、R_H 和 R_A 的 84.7%、68.3%、5.1%，分别解释重度干扰林 R_S、R_H 和 R_A 的 84.4%、54.6%、21.7%.

轻度干扰林和重度干扰林 0～10 cm 土层土壤含水量季节波动幅度较大，2 种林分最高值分别出现在 7 月上旬和 8 月上旬，最低值均出现在 10 月，其变化范围分别 5.3%～22.3%和 5.4%～26.8%；2 种林分土壤含水量的年平均值表现为轻度干扰林(15.4%)大于重度干扰林(13.2%)，二者差异显著.表 4 显示，轻度干扰林的 R_S 和 R_H 与土壤含水量呈显著正相关，而重度干扰林仅 R_S 与土壤含水量呈显著正相关.

利用土壤温度和含水量进行非线性模型拟合发

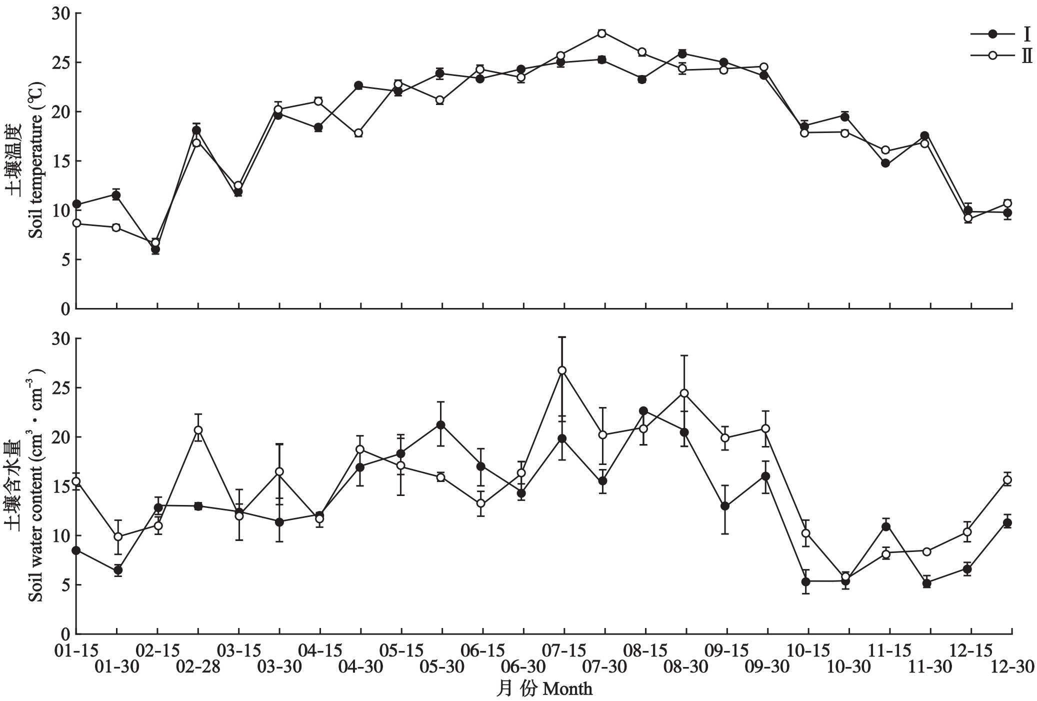

图 3　米槠轻度干扰林和重度干扰林土壤温度和含水量年动态

Fig.3　Annual dynamics of soil temperature and water content in *Castanopsis carlesii* forest with low interference and high interference.

表 3　土壤呼吸速率和土壤温度的回归方程及 Q_{10} 值

Table 3　Regression models of soil respiration rate with soil temperature and Q_{10} values

研究对象 Study object	组分 Component	$R_S=ae^{bt}$				Q_{10}
		a	b	R^2	P	
米槠轻度干扰林	R_S	1.101	0.056	0.847**	0.00	1.75
Castanopsis carlesii forest	R_H	0.670	0.066	0.683**	0.00	1.93
with low interference	R_A	0.414	0.024	0.051	0.29	1.27
米槠重度干扰林	R_S	0.467	0.090	0.844**	0.00	2.46
Castanopsis carlesii forest	R_H	0.382	0.085	0.546**	0.00	2.34
with high interference	R_A	0.139	0.050	0.217*	0.02	1.65

* $P<0.05$; ** $P<0.01$. 下同 The same below.

现(表 5),土壤温度和含水量共同解释轻度干扰林 R_S、R_H 及 R_A 的 85.2%、73.8%和 5.8%,重度干扰林的 79.9%、55.4%和 21.6%.总体与仅考虑温度的非线性模型拟合结果相差不大,说明在 2 种林分中,土壤呼吸虽然受到水分的一定影响,但对它起主要作用的仍是土壤温度.根据表层 5 cm 深土壤温度计算出土壤呼吸的 Q_{10} 值,结果显示,轻度干扰林和重度干扰林 R_S、R_H、R_A 的 Q_{10} 值分别为 1.75、1.93、1.27 和 2.46、2.34、1.65,其中重度干扰林的 Q_{10} 值总体上高于轻度干扰林,且 2 种林分 R_H 的 Q_{10} 值均大于 R_A 的 Q_{10} 值(表 3).

表 4　土壤呼吸速率和水分的回归方程

Table 4　Regression models of soil respiration rate with soil water content

研究对象 Study object	组分 Component	$R_S=aW+b$			
		a	b	R^2	P
米槠轻度干扰林	R_S	0.127	1.655	0.363**	0.002
Castanopsis carlesii forest	R_H	0.106	1.156	0.257*	0.011
with low interference	R_A	0.021	0.500	0.054	0.273
米槠重度干扰林	R_S	0.142	0.666	0.302**	0.005
Castanopsis carlesii forest	R_H	0.075	1.155	0.094	0.144
with high interference	R_A	0.022	0.090	0.161	0.052

表 5　土壤呼吸速率与土壤温度、土壤水分的回归方程

Table 5　Regression models of soil respiration rate with soil temperature and soil water content

研究对象 Study object	组分 Component	$R_S=ae^{bt}W^c$				
		a	b	c	R^2	P
米槠轻度干扰林	R_S	1.070	0.058	0.00	0.852**	0.00
Castanopsis carlesii forest	R_H	0.582	0.074	0.00	0.738**	0.00
with low interference	R_A	0.365	0.011	0.22	0.058	0.50
米槠重度干扰林	R_S	0.630	0.077	0.00	0.799**	0.00
Castanopsis carlesii forest	R_H	0.552	0.073	0.00	0.554**	0.00
with high interference	R_A	0.078	0.032	0.41	0.216*	0.04

3 讨 论

3.1 温度和水分对土壤呼吸及其组分的影响

土壤温度和含水量是调控土壤呼吸最重要的影响因子,其通过对微生物活性[13]、植物根系生长及光合作用的调节,进而影响土壤呼吸及其组分的变化[14].本研究中,除轻度干扰林的 R_A外,2 种林分的 R_S、R_H以及重度干扰林的 R_A均与土壤温度呈显著的指数关系;而轻度干扰林的 R_S、R_H以及重度干扰林的 R_S与土壤水分具有显著线性关系,但轻度干扰林的 R_A以及重度干扰林的 R_H与土壤水分之间未达到显著相关.这与当前多数研究结果一致[11,15].本研究中,轻度干扰林的 R_A未受土壤温度、水分的影响,而重度干扰林的 R_A则与土壤温度显著相关,与土壤含水量也存在较明显的相关性(表 4),说明 2 种林分间 R_A差异可能是由于植物根系对土壤温度和含水量响应不同所致,因为轻度干扰林的林分郁闭度较重度干扰林高,林内温度、水分等环境因子相对稳定;其次,轻度干扰林的群落组成更为丰富,植物地上及地下部分,尤其是根系发育较好(表 1),从而使得轻度干扰林的 R_A更多地受到光合产物及根系活性的调控[16].

本研究中,林分土壤呼吸及其各组分的 Q_{10}值分别为 1.75、1.93、1.27 和 2.46、2.34、1.65.除轻度干扰林 R_A的 Q_{10}值外,所得结果与陈光水等[17]得出的我国森林土壤呼吸 Q_{10}值为 1.33~5.53 的结论相符,与 Zheng 等[18]报道的我国亚热带森林土壤呼吸 Q_{10}值为 1.56~2.39 的结论相差不大.本研究中,重度干扰林的 Q_{10}值均大于轻度干扰林,表明土壤呼吸温度敏感性随干扰强度的增加而变大,这与其他研究结果一致[19-20].这可能是因为人为干扰强度的增加使土壤中有机质分解及微生物活性加快,进而刺激到土壤温度的敏感性[21].这也说明轻度干扰的森林生态系统可能比重度干扰的森林生态系统更加稳定,不易受外界环境变化的影响.此外,2 种林分 R_H的 Q_{10}值大于 R_A的 Q_{10}值,这与部分研究结果相反[11,22],但与另外一些研究结果一致[23-24].其原因可能是因为 2 种呼吸组分本身对温度敏感程度的内在差异以及各自所占的比例差异导致的[25].

3.2 土壤呼吸动态及其组分所占的比例

本研究中,2 种林分的 R_S、R_H、R_A均表现出明显的季节变化,其中 R_S、R_H在夏末时处于较高水平,而 R_A分别在春季和夏季达到 2 次较明显的峰值.这可能是由于本地区典型的季风气候,即夏季雨热同期的优势使得土壤中微生物活跃异常,同时充足的光热条件也使得植物根系活性及光合作用显著,从而使这一时段的土壤呼吸及其组分明显高于其他时段.此外,自养呼吸还在春季达到一个较高水平[26-27],其原因可能是因为春季植物根系处于旺盛的生长时期,根系对碳水化合物的利用显著[28].

关于自养和异养组分对土壤呼吸的贡献,众多学者对我国不同气候带的森林系统进行了研究(表 6),结果发现异养组分对土壤呼吸的贡献率为 47.1%~83.6%.

由表 6 可知,从南到北我国不同气候带的森林生态系统多以 R_H居于主导地位,即 R_H对 R_S的贡献率大于自养呼吸.此外,根据 Wang 等[22]对全球范围内的森林生态系统呼吸数据整理发现,R_H对 R_S贡献率为 13.4% ~ 94.0%.本研究中,轻度干扰林和重度干扰林的 R_H比例分别为 76.6%和 83.6%,较好地落在该范围内,并且重度干扰林的异养组分贡献比例大于轻度干扰林,这可能是由于重度干扰林中对部分树种的定期采伐使得林分郁闭度降低,光照对地面的照射作用增加,进而加速了土壤中微生物对碳的分解[33];其次采伐后剩余物的保留对于林分枯枝落叶层的碳素供应在短期内起到了加强效果[34];而细根生物量的减少导致土壤 R_A下降,可能也是导致重度干扰林 R_H比例较大的原因之一.

吴君君等[11]通过对不同气候带森林土壤呼吸数据的收集,得到 R_A对 R_S的贡献率为 18.4% ~ 83.0%.本研究中,轻度干扰林 R_A比例显著高于重度干扰林,其中轻度干扰林的 R_A比例(23.4%)较好地落入该范围内,而重度干扰林的 R_A比例(16.4%)明显低于该范围的最低值.这可能与外在的人为干扰造成了 2 种林分树种丰富度差异有关[35],因为重度干扰林中定期的择伐导致植被地下根系大量死亡,使得 R_A通量显著降低[33].相反,轻度干扰林由于人为破坏较少,植被细根丰富,R_A通量较大,因此轻度干扰林 R_A比例显著高于重度干扰林.

3.3 土壤呼吸各组分的影响因素

土壤呼吸除受到温度、含水量等非生物因子调控外,还受到土壤微生物、植物等生物因子的影响[36-37].其中,R_A速率多取决于所在林分的生产力水平[38],生产力水平越高,植物凭借光合作用固定并通过树干输送到根系的含碳物质越多[39],进而对 R_A的刺激作用更显著;有研究表明,外在的干扰胁迫程度越低,植物根系对光合作用同化所得的碳水化合物的利用度越高,根系排放CO_2越多[40].另外,

表 6　中国不同气候带森林土壤呼吸速率年均值及异养呼吸的贡献比例

Table 6　Contribution ratio of heterotrophic respiration and annual mean to forest soil respiration rate in different climate zones in China

气候带 Climate zone	研究地点 Study site	植被类型 Vegetation type	土壤呼吸速率年平均值 Annual mean of soil respiration rate ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	R_H/R_S (%)	文献 Reference
热带	云南西双版纳	橡胶林 Rubber plantation	2.06	58.0	[29]
Tropical zone	Xishuangbanna, Yunnan	季雨林 Seasonal rain forest	2.66	71.0	[29]
亚热带	广东鼎湖山	马尾松林 *Pinus massoniana* forest	3.25	60.5	[30]
Subtropical zone	Dinghushan,	针阔叶混交林 Coniferous and broad-leaved mixed forest	3.17	66.7	[30]
	Guangdong	季风常绿阔叶林 Monsoon evergreen broad-leaved forest	3.75	55.5	[30]
	福建三明	米槠人工林 *Castanopsis carlesii* plantation	3.48	67.5	[11]
	Sanming, Fujian	杉木人工林 *Cunninghamia lanceolata* plantation	2.45	75.9	[11]
	福建三明	米槠轻度干扰林 *C. carlesii* forest with low interference	3.32	76.6	本研究
	Sanming, Fujian	米槠重度干扰林 *C. carlesii* forest with high interference	2.86	83.6	本研究
亚热带-温带过渡带	河南内乡	阔-阔混交林 Broad-leaved mixed forest	2.82	61.9	[31]
Transitional area from	Neixiang, Henan	锐齿栎老林 *Quercus aliena* var. *acuteserrata* mature forest	2.45	60.2	[31]
the subtropics to		栓皮栎林 *Quercus variabilis* forest	2.71	56.7	[31]
temperate		针-阔混交林 Coniferous and broad-leaved mixed forest	2.52	55.8	[31]
		锐齿栎幼林 *Quercus aliena* young forest	3.28	47.1	[31]
温带	黑龙江尚志	硬阔叶林 Hard-wood forest	3.61	53.8	[32]
Temperate zone	Shangzhi,	杨桦林 Poplar-birch forest	3.70	55.5	[32]
	Heilongjiang	杂木林 Mixed-wood forest	3.94	59.9	[32]
		蒙古栎林 Mongolian oak forest	3.79	64.1	[32]
		红松林 Korean pine plantation	3.05	65.0	[32]
		落叶松林 Dahurian larch plantation	2.35	71.2	[32]

林分生产力水平越高，根系的生长状况越好，R_A越大[41]. 王韦韦等[12]研究发现，轻度干扰林的根系生物量及空间形态明显优于重度干扰林. 由于轻度干扰林受干扰程度较低，其地上及地下部分的生产力水平均高于重度干扰林，因而轻度干扰林表现出具有较高的 R_A.

土壤呼吸中的异养组分主要受土壤有机碳含量及凋落物量调控[42-43]. 凋落物作为森林养分归还的一种重要载体，其分解速率对 R_S有显著影响[44-47]. 有研究表明，凋落物对 R_S的影响，既反映在凋落物的数量方面，同时在凋落物的质量方面也有所体现[48]. 本研究中，2 种林分均为米槠林人促更新林，因而凋落物对土壤呼吸影响的差异主要体现在凋落物的数量方面. 本研究中，重度干扰林因受外在的干扰强度较大，其林分内的植物群落丰富度不及轻度干扰林，凋落物的归还量显著低于轻度干扰林(表 1)，因此这可能是导致重度干扰林 R_S，尤其是 R_H明显低于轻度干扰林的原因之一. 此外，土壤自身的物理性状差异也会对 R_S产生直接或间接的影响[49]. 与重度干扰林相比，轻度干扰林土壤容重较低(表 1)，土壤透气、透水性均优于重度干扰林，因此在同等条件下，轻度干扰林具有较高的 CO_2扩散速率，这可能也是导致轻度干扰林呼吸高于重度干扰林的另一原因.

参考文献

[1] Tang JW, Baldocchi DD, Xu LK. Tree photosynthesis modulates soil respiration on a diurnal time scale. *Global Change Biology*, 2005, **11**: 1298-1304

[2] Bond-Lamberty B, Thomson A. Temperature-associated increases in the global soil respiration record. *Nature*, 2010, **464**: 579-583

[3] Reichstein M, Rey A, Freibauer A, *et al*. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. *Global Biogeochemistry Cycles*, 2003, **17**: 1104-1119

[4] Kuzyakov Y. Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology and Biochemistry*, 2006, **38**: 425-488

[5] Craine JM, Fierer N, McLauchlan K. Widespread coupling between the rate and temperature sensitivity of organic matter decay. *Nature Geoscience*, 2010, **3**: 854-857

[6] Schaefer DA, Feng WT, Zou XM. Plant carbon inputs and environmental factors strongly affect soil respiration in a subtropical forest of southwestern China. *Soil Biology and Biochemistry*, 2009, **41**: 1000-1007

[7] Huang Q-L (黄清麟), Li Y-H (李元红). Comparison between natural broad-leaved forest and man-made forest in Fujian Province. Ⅰ. Conservation and maintenance

of soil and water resources. *Journal of Mountain Science* (山地学报), 2000, **18**(1): 69-75 (in Chinese)

[8] Qiu R-H (邱仁辉), Yang Y-S (杨玉盛), Peng J-C (彭加才), *et al*. Comparison of productivity and soil fertility between the *Castanopsis carlesii* community with artificial measures promoting regeneration and *Cunninghamia lanceolata* plantation. *Journal of Mountain Science* (山地学报), 2001, **19**(1): 33-37 (in Chinese)

[9] Chen S-S (陈绍栓), Chen S-R (陈淑容), Ma X-Q (马祥庆). Effects of different regeneration pattern of secondary broadleaved forest on stand composition and soil fertility. *Scientia Silvae Sinicae* (林业科学), 2001, **37**(6): 113-117 (in Chinese)

[10] Subke JA, Inglima I, Cotrufo MF. Trends and methodological impacts in soil CO_2 efflux partitioning: A meta-analytical review. *Global Change Biology*, 2006, **12**: 921-943

[11] Wu J-J (吴君君), Yang Z-J (杨智杰), Liu X-F (刘小飞), *et al*. Analysis of soil respiration and components in *Castanopsis carlesii* and *Cunninghamia lanceolata* plantations. *Chinese Journal of Plant Ecology* (植物生态学报), 2014, **38**(1): 45-53 (in Chinese)

[12] Wang W-W (王韦韦), Huang J-X (黄锦学), Chen F (陈 锋), *et al*. Effects of tree species diversity on fine-root biomass and morphological characteristics in subtropical *Castanopsis carlesii* forests. *Chinese Journal of Applied Ecology* (应用生态学报), 2014, **25**(2): 318-324 (in Chinese)

[13] Mikan CJ, Schimel JP, Doyle AP. Temperature controls of microbial respiration in arctic tundra soils above and below freezing. *Soil Biology and Biochemistry*, 2002, **34**: 1785-1795

[14] Moyano FE, Kutsch WL, Rebmann C. Soil respiration fluxes in relation to photosynthetic activity in broad-leaf and needle-leaf forest stands. *Agricultural and Forest Meteorology*, 2008, **148**: 135-143

[15] Sulzman EW, Brant JB, Bowden RD, *et al*. Contribution of aboveground litter, belowground litter, and rhizosphere respiration to total soil CO_2 efflux in an old growth coniferous forest. *Biogeochemistry*, 2005, **73**: 231-256

[16] Kuzyakov Y. Review: Factors affecting rhizosphere priming effects. *Journal of Plant Nutrition and Soil Science*, 2002, **165**: 382-396

[17] Chen G-S (陈光水), Yang Y-S (杨玉盛), Lv P-P (吕萍萍), *et al*. Regional patterns of soil respiration in China's forests. *Acta Ecologica Sinica* (生态学报), 2008, **28**(4): 1748-1761 (in Chinese)

[18] Zheng ZM, Yu GR, Fu YL, *et al*. Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: A trans-China based case study. *Soil Biology and Biochemistry*, 2009, **41**: 1531-1540

[19] Yan JH, Zhang DQ, Zhou GY, *et al*. Soil respiration associated with forest succession in subtropical forests in Dinghushan Biosphere Reserve. *Soil Biology and Biochemistry*, 2009, **41**: 991-999

[20] Sheng H, Yang YS, Yang ZJ, *et al*. The dynamic response of soil respiration to land-use changes in subtropical China. *Global Change Biology*, 2010, **16**: 1107-1121

[21] McCulley RL, Boutton TW, Archer SR. Soil respiration in a subtropical savanna parkland: Response to water additions. *Soil Science Society of America Journal*, 2007, **71**: 820-828

[22] Wang W, Chen WL, Wang SP. Forest soil respiration and its heterotrophic and autotrophic components: Global patterns and responses to temperature and precipitation. *Soil Biology and Biochemistry*, 2010, **42**: 1236-1244

[23] Hartley IP, Heinemeyer A, Evans SP, *et al*. The effect of soil warming on bulk soil vs. rhizosphere respiration. *Global Change Biology*, 2007, **13**: 2654-2667

[24] Jiang Y (姜 艳). Spatial and Temporal Variation of the Soil Respiration and Its Three Biological Processes in *Phyllostachys edulis* Plantations. PhD Thesis. Beijing: Chinese Academy of Forestry, 2010 (in Chinese)

[25] Yang Q-P (杨庆朋), Xu M (徐 明), Liu H-S (刘洪升), *et al*. Impact factors and uncertainties of the temperature sensitivity of soil respiration. *Acta Ecologica Sinica* (生态学报), 2011, **31**(8): 2301-2311 (in Chinese)

[26] Yang YS, Chen GS, Lin P, *et al*. Fine root distribution, seasonal pattern and production in four plantations compared with a natural forest in subtropical China. *Annals of Forest Science*, 2004, **61**: 617-627

[27] Yang Y-S (杨玉盛), Chen G-S (陈光水), He Z-M (何宗明), *et al*. Net productivity and turnover rate of fine roots in mixed forest of *Cunninghamia lanceolata* and *Tsoongiodendron odorum*. *Scientia Silvae Sinicae* (林业科学), 2001, **37**(1): 35-41 (in Chinese)

[28] Xiong D-C (熊德成), Huang J-X (黄锦学), Chen G-S (陈光水), *et al*. A preliminary report on the fine root exudate of *Castanopsis carlesii* and *Cunninghamia lanceolata* in subtropical zone. *Journal of Subtropical Resources and Environment* (亚热带资源与环境学报), 2015, **10**(1): 83-86 (in Chinese)

[29] Lu H-Z (卢华正), Sha L-Q (沙丽清), Wang J (王君), *et al*. Seasonal variation of soil respiration and its components in tropical rain forest and rubber plantation in Xishuangbanna, Yunnan. *Chinese Journal of Applied Ecology* (应用生态学报), 2009, **20**(10): 2315-2322 (in Chinese)

[30] Han T-F (韩天丰), Zhou G-Y (周国逸), Li Y-L (李跃林), *et al*. Partitioning soil respiration in lower subtropical forests at different successional stages in southern China. *Chinese Journal of Plant Ecology* (植物生态学报), 2011, **35**(9): 946-954 (in Chinese)

[31] Chang J-G (常建国), Liu S-R (刘世荣), Shi Z-M (史作民), *et al*. Soil respiration and its components partitioning in the typical forest ecosystems at the transitional area from the northern subtropics to warm temperate, China. *Acta Ecologica Sinica* (生态学报), 2007, **27**(5): 1791-1802 (in Chinese)

[32] Yang J-Y (杨金艳), Wang C-K (王传宽). Partitioning soil respiration of temperate forest ecosystems in Northeastern China. *Acta Ecologica Sinica* (生态学报), 2006, **26**(6): 1640-1647 (in Chinese)
[33] Meng C (孟　春), Wang L-H (王立海), Shen W (沈　微). Effect of sensitivity of soil respiration to soil temperature in a conifer-broadleave forest in Xiaoxing'an Mountain after select cutting. *Scientia Silvae Sinicae* (林业科学), 2011, **47**(3): 102-106 (in Chinese)
[34] Meng C (孟　春), Wang L-H (王立海), Shen W (沈　微). Effect of selective cutting on soil partitioning respiration in a conifer-broadleaved forest during growing season. *Scientia Silvae Sinicae* (林业科学), 2008, **44**(8): 23-28 (in Chinese)
[35] Yu L-F (喻理飞), Zhu S-Q (朱守谦), Ye J-Z (叶镜中), *et al*. Evaluation on degradation of Karst forest community and human disturbance. *Chinese Journal of Applied Ecology* (应用生态学报), 2002, **13**(5): 529-532 (in Chinese)
[36] Dijkstra FA, Cheng W. Interactions between soil and tree roots accelerate long-term soil carbon decomposition. *Ecology Letters*, 2007, **10**: 1046-1053
[37] Burns RG, DeForest JL, Marxsen J, *et al*. Soil enzymes in a changing environment: Current knowledge and future directions. *Soil Biology and Biochemistry*, 2013, **58**: 216-234
[38] Janssens IA, Carrara A, Ceulemans R. Annual Q_{10} of soil respiration reflects plant phenological patterns as well as temperature sensitivity. *Global Change Biology*, 2004, **10**: 161-169
[39] Kuzyakov Y, Gavrichkova O. Time lag between photosynthesis and carbon dioxide efflux from soil: A review of mechanisms and controls. *Global Change Biology*, 2010, **16**: 3386-3406
[40] Gaumont-Guay D, Black TA, Barr AG, *et al*. Biophysical controls on rhizospheric and heterotrophic components of soil respiration in a boreal black spruce stand. *Tree Physiology*, 2008, **28**: 161-171
[41] Fu S, Cheng W, Susfalk R. Rhizosphere respiration varies with plant species and phenology: A greenhouse pot experiment. *Plant and Soil*, 2002, **239**: 133-140
[42] Adachi M, Bekku YS, Rashidah W, *et al*. Differences in soil respiration between different tropical ecosystems. *Applied Soil Ecology*, 2006, **34**: 258-265
[43] Wang Q-K (王清奎). Responses of forest soil carbon pool and carbon cycle to the changes of carbon input. *Chinese Journal of Applied Ecology* (应用生态学报), 2011, **22**(4): 1075-1081 (in Chinese)
[44] Yang W-Q (杨万勤), Deng R-J (邓仁菊), Zhang J (张　健). Forest litter decomposition and its responses to global climate change. *Chinese Journal of Applied Ecology* (应用生态学报), 2007, **18**(12): 2889-2895 (in Chinese)
[45] Yang Y-S (杨玉盛), Chen G-S (陈光水), Lin P (林鹏), *et al*. Fine root distribution, seasonal pattern and production in a native forest and monoculture plantations in subtropical China. *Acta Ecologica Sinica* (生态学报), 2003, **23**(9): 1719-1730 (in Chinese)
[46] Li T-Y (立天宇), Kang F-F (康峰峰), Han H-R (韩海荣), *et al*. Responses of soil microbial carbon metabolism to the leaf litter composition in Liaohe River Nature Reserve of northern Hebei Province, China. *Chinese Journal of Applied Ecology* (应用生态学报), 2015, **26**(3): 715-722 (in Chinese)
[47] Sayer EJ, Tanner EVJ. Experimental investigation of the importance of litterfall in lowland semi-evergreen tropical forest nutrient cycling. *Journal of Ecology*, 2010, **98**: 1052-1062
[48] Huang Z, Wan X, He Z, *et al*. Soil microbial biomass, community composition and soil nitrogen cycling in relation to tree species in subtropical China. *Soil Biology and Biochemistry*, 2013, **62**: 68-75
[49] He N (何　娜), Wang L-H (王立海), Meng C (孟春). Effect of compaction on diurnal variation of soil respiration in *Larix gmellinii* plantation in summer. *Chinese Journal of Applied Ecology* (应用生态学报), 2007, **18**(12): 2889-2895 (in Chinese)

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Chen Z, Lin C-F, Zhang X-X, *et al*. Effects of interference intensity on soil respiration and its components in *Castanopsis carlesii* forest with artificially assisted regeneration in subtropical China. *Chinese Journal of Applied Ecology*, 2017, **28**(1): 19-27 (in Chinese)