DOI：10.13287/j.1001-9332.2009.0219
应用生态学报 2009年6月 第20卷 第6期
Chinese Journal of Applied Ecology, Jun. 2009, 20(6): 1285-1292

长白山阔叶红松林生态系统碳动态及其对气候变化的响应*

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摘 要 应用基于干物质生产理论的过程模型(Sim-CYCLE)估算了1982—2003年间长白山阔叶红松林生态系统总第一生产力(GPP)、净第一生产力(NPP)、净生态系统生产力(NEP)及其季节动态变化以及碳储量(WE)、植物碳储量(WP)和土壤碳储量(WS)，并分析了这些指标在当前气候情景和碳平衡情况时的差异及其对未来气候变化情景的响应．结果表明：在当前气候情景下，长白山阔叶红松林GPP、NPP和NEP分别为14.9、8.7和2.7 Mg C·hm^{-2}·a^{-1}，三者分别比实测值减少2.8 Mg C·hm^{-2}·a^{-1}、增加1.4 Mg C·hm^{-2}·a^{-1}和增加0.2 Mg C·hm^{-2}·a^{-1}；长白山阔叶红松林6—8月的NEP占全年总量的90%以上，其中，7月最高(1.23 Mg C·hm^{-2}·month^{-1})；研究区WE、WP和WS分别为550.8、183.8和367.0 Mg C·hm^{-2}，其与实测值均具有较高的一致性．从当前气候情景下到达碳平衡前，长白山阔叶红松林碳储量均有不同程度的增加，GPP和NPP分别为17.7和7.3 Mg C·hm^{-2}·a^{-1}，表明研究区碳"汇"的作用随着碳储量的增加逐渐减弱；温度增加2℃时，不利于长白山阔叶红松林GPP、NPP和NEP的增长，CO_2浓度倍增则可有利地促进三者的增长，CO_2浓度倍增、温度增加2℃对GPP、NPP和NEP增幅的影响与单纯CO_2浓度倍增的影响相似，气候变化情景对长白山阔叶红松林碳储量的影响规律与对生产力幅度的影响相同，这可能是生态系统生产力影响碳积累所致．

关键词 长白山 阔叶红松林 净第一性生产力 碳收支 气候变化 模拟
文章编号 1001-9332(2009)06-1285-08 **中图分类号** S718.5 **文献标识码** A

Carbon dynamics of broad-leaved Korean pine forest ecosystem in Changbai Mountains and its responses to climate change. TANG Feng-de[1,2], HAN Shi-jie[2], ZHANG Jun-hui[2] ([1]College of Environmental Sciences, Liaoning University, Shenyang 110036, China; [2]Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China). -Chin. J. Appl. Ecol., 2009, 20(6): 1285-1292.

Abstract: By using process model Sim-CYCLE based on dry matter production theory, this paper estimated the gross primary productivity (GPP), net primary productivity (NPP), net ecosystem productivity (NEP), ecosystem carbon storage (WE), total plant carbon storage (WP), and total soil carbon storage (WS) of broad-leaved Korean pine forest ecosystem in Changbai Mountains from 1982 to 2003, and analyzed the variations of these indices under present climate condition and carbon equilibrium state as well as the responses of these indices to climate change scenarios in the future. Under present climate condition, the estimated GPP, NPP, and NEP were 14.9, 8.7, and 2.7 Mg C·hm^{-2}·a^{-1}, being 2.8 Mg C·hm^{-2}·a^{-1} less and 1.4 and 0.2 Mg C·hm^{-2}·a^{-1} higher than the measured values, respectively. The NEP in June—August occupied more than 90% of the annual NEP, and the maximum monthly NEP appeared in July (1.23 Mg C·hm^{-2}·month^{-1}). The estimated WE, WP, and WS were 550.8, 183.8, and 367.0 Mg C·hm^{-2}, respectively, very close to the measured values. From present climate condition to carbon equilibrium state, the estimated carbon storages of the forest ecosystem increased to some extent, with the GPP

* 中国科学院知识创新工程重要方向项目(KZCX2-YW-416)资助．
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2008-12-02收稿，2009-03-30接受．

and NPP being 17.7 and 7.3 Mg C · hm^{-2} · a^{-1}, respectively, suggesting that the role of the forest ecosystem as a carbon "sink" declined gradually with the increase of carbon storage. A 2 ℃ -increment of air temperature did not benefit the increase of GPP, NPP and NEP, while doubling CO_2 concentration was in adverse. The effects of the combination of doubling CO_2 concentration and 2 ℃ -increment of air temperature on the GPP, NPP, and NEP were similar to those of doubling CO_2 concentration. The climate change scenario in the future had the same effects both on the carbon storage and on the productivity of the forest ecosystem, which was mainly correlated to the effects of primary productivity on the carbon storage.

Key words: Changbai Mountains; broad-leaved Korean pine forest; net primary productivity; carbon budget; climate change; simulation.

森林生态系统是主要的陆地生态系统之一，也是最复杂的陆地生态系统，它具有很高的生物生产力和生物量．虽然森林面积仅占陆地面积的 26%，但其碳储量占整个陆地生态系统的 80%以上，而且森林每年碳固定量约占整个陆地生态系统碳的 2/3 以上[1-2]．大气 CO_2 浓度增加所引起的全球变暖将对陆地生态系统造成一系列严重影响，而陆地生态系统生理过程的任何变化也会影响大气中 CO_2 浓度水平[1-2]，这些变化已通过大气 CO_2 浓度的季节和年变异得以反映[3-4]．因此，作为大气 CO_2 汇的森林生态系统的作用一直是陆地生态系统碳动态的研究热点[5-6]．目前，关于大气与生物圈 CO_2 交换以及陆地生态系统碳循环的模型已有诸多尝试，全球尺度的模拟模型需要较少的参数和输入较少的数据[7-9]，而样地尺度的碳循环模型结构复杂、参数量大[10-12]，虽然后者表现出很高的精度，但其可操作性较低[11-12]．

长白山阔叶红松林是研究全球变化的中国东北样带，也是 China-FLUX 的观测站点之一[13]．目前，基于过程模型在区域尺度上对长白山森林生态系统的生产力及其对气候变化的响应研究已有一些报道[14-18]，采用涡度相关法对长白山阔叶红松林样地的生产力研究也已初步进行[19-22]．本文试图采用陆地生态系统生理生态过程模型 Sim-CYCLE[3]，在样地尺度上模拟了 1982—2003年间长白山阔叶红松林净第一性生产力和碳平衡的变化，旨在深入了解长白山阔叶红松林植被生产力的变化过程，为研究全球气候变化条件下，合理估算长白山阔叶红松林森林生态系统碳吸收的能力及未来动态提供科学依据．

1 研究地区与研究方法

1.1 研究区概况

本研究选择的森林生态系统为位于吉林省东南部的长白山自然保护区内（41°42′—42°25′ N, 127°38′—128°16′ E）的阔叶红松林．研究区属温带大陆性山地气候，年均温度约 3.6 ℃，年均降水量 695 mm，无霜期约 140 d，日照时数 1800～2300 h．该区地带性土壤为山地暗棕色森林土，主要优势树种为红松（*Pinus koraiensis*）、椴树（*Tilia amurensis*）、蒙古栎（*Quercus mongolica*）、水曲柳（*Fraxinus mandshurica*）和色木槭（*Acer mono*）等[23]．林分为复层异龄林，林分平均高度为 26 m，立木株数 560株 · hm^{-2}，优势树种平均年龄约 200 a[19]．

1.2 研究方法

1.2.1 Sim-CYCLE模型 Sim-CYCLE模型（simulation model of carbon cycle in land ecosystems）是基于干物质生产理论并已成功应用于森林和草地等陆地生态系统的生理生态过程模型[24-25]，模型的构建机理见文献[26—27]．该模型可以月为单位对生态系统进行有效模拟计算，进而模拟陆地生态系统的季节、年际间的碳动态[28-30]．在模型运行过程中，假设稳定的大气 CO_2 含量为 360 μmol · mol^{-1}[31]，主要对土壤碳储量、净初级生产力（NPP）、净生态系统生产力（NEP）、叶面积指数（LAI）等参数进行模拟．陆地生态系统叶、干、根、凋落物和矿质土壤各分室在模型运算开始的幼年期初始碳为 0.1 Mg C · hm^{-2}（1 Mg=10^6 g），当陆地生态系统 NEP<0.0001 Mg C · hm^{-2} · a^{-1}，即达到碳平衡状态，可认定该生态系统达到顶极阶段[32]．

1.2.2 数据来源 本研究数据来自长白山保护区周围的 3个气象站和中国科学院长白山森林生态系统定位站 1982—2003年的气象数据，对一些不符合模型要求的基础数据采用插值法得到．根据相关文献得知，研究区根系深度 90 cm[33]、土壤持水量 280 mm[34]、水力传导度 3.75×10^{-3} m · d^{-1}[35]．对上述基础数据进行标准化得到模型植物参数和土壤参数的标准数值（表 1）．

表 1 长白山阔叶红松林样地的参数标准值

Tab. 1 Site-specific parameter values in sampling site of broad-leaved Korean pine forests at Changbai Mountains

模型参数 Model parameter	单位 Unit	参数值 Parameter value	模型参数 Model parameter	单位 Unit	参数值 Parameter value
ALF	—	0.15	$SARM_C$	$Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.0101
CV	—	0.85	$SARM_R$	$Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.3536
KA_O	—	0.46	SLF_F	$\times 10^{-3} Mg C \cdot Mg^{-1} C \cdot d^{-1}$	1.20
KM_{AE}	—	0.25	SLF_C	$\times 10^{-3} Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.0368
KM_{CD}	—	40	SLF_R	$\times 10^{-3} Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.2212
PC_{SATO}	$\mu mol\ photon \cdot m^{-2} \cdot s^{-1}$	14	T_{OPT}	℃	20
QE_0	$mol\ CO_2 \cdot mol^{-1}$ photon	0.05	T_{MIN}	℃	−2
QT	—	2	T_{MAX}	℃	40
$SARG_F$	$Mg C \cdot Mg^{-1} C$	0.38	KM_{SW}	—	0.15
$SARG_C$	$Mg C \cdot Mg^{-1} C$	0.20	KM_{WA}	—	0.08
$SARG_R$	$Mg C \cdot Mg^{-1} C$	1.44	SHR_L	$Mg C \cdot Mg^{-1} C \cdot d^{-1}$	1.08
$SARM_F$	$Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.1160	SHR_H	$Mg C \cdot Mg^{-1} C \cdot d^{-1}$	0.72

ALP：叶面反射率 Albedo of leaf surface; CV：蒸散可用水速率曲线凸度 Convexity of water availability-evapotranspiration rate curve; KA_O：消光系数 Light attenuation coefficient; KM_{AE}, KM_{CD}：Michelis方程参数 Parameters in Michelis-type equation parameter; PC_{SATO}：光饱和速率 Light-saturated photosynthetic rate; QE_0：光量子产量 Quantum yield; QT：呼吸温度敏感性 Temperature sensitivity of respiration; $SARG_F$：叶子比生长呼吸速率 Specific growth respiration of leaf; $SARG_C$：枝干比生长呼吸速率 Specific growth respiration of stem and branch; $SARM_R$：根比生长呼吸速率 Specific growth respiration of root system; $SARM_F$：叶子比维持呼吸速率 Specific maintenance respiration rate of leaf; $SARM_C$：枝干比维持呼吸速率 Specific maintenance respiration rate of stem and branch; $SARM_R$：根系比维持呼吸速率 Specific maintenance respiration of root system; SLF_F：叶子比凋落速率 Specific litter fall rate of leaf; SLF_C：枝干比凋落速率 Specific litter fall rate of stem and branch; SLF_R：根比凋落速率 Specific litter fall rate of root system; T_{OPT}：光合最适温度 Optimum temperature for photosynthesis; T_{MIN}：光合最低温度 Minimum temperature for photosynthesis; T_{MAX}：光合最高温度 Maximum temperature for photosynthesis; KM_{SW}：Michelis方程参数 Parameter in Micielis-type equation; KM_{WA}：Michelis方程参数 Parameter in Michelis-type equation; SHR_L：凋落物比异氧呼吸速率 Specific litter heterotrophic respiration rate; SHR_H：矿质土壤比异氧呼吸速率 Specific mineral soil heterotrophic respiration rate

1.3 数据处理

采用 Microsoft Excel软件计算 1982—2003年研究区各站点的气象和土壤等各环境参数的初始化数值和植被碳动态数值.

2 结果与分析

2.1 当前气候情景下长白山阔叶红松林生态系统碳动态的模拟

2.1.1 现时长白山阔叶红松林生态系统碳动态的模拟 由表 2可以看出，1982—2003年间，长白山阔叶红松林植被碳储量 (WP)模拟值为 146.9 $Mg C \cdot hm^{-2}$，其中枝干碳储量 (WP_C)、根碳储量 (WP_R)和叶碳储量 (WP_F)的模拟值分别为 120.9、23.9和 2.1 $Mg C \cdot hm^{-2}$. 根据长白山阔叶红松林样地实测的森林生物量[36]和生物量转换碳储量系数 (0.45)[37]，得到研究区 WP为 147.94 $Mg C \cdot hm^{-2}$，其中 WP_C、WP_R和 WP_F分别为 120.91、23.87和 3.16 $Mg C \cdot hm^{-2}$. 由此可知，研究区 WP的模拟值与实测值具有较高的一致性. 该区土壤碳储量 (WS)模拟值为 287.8 $Mg C \cdot hm^{-2}$，而根据研究区土壤平均碳含量、土壤厚度[38]和土壤容重[39]计算得到土壤碳密度为 319.9 $Mg C \cdot hm^{-2}$. 研究区 LAI模拟值为 4.7～5.5，与关德新等[40]的 LAI实测值基本一致. 本文中土壤周转率模拟值为 32.8 a，与邵月红等[41]的结果范围基本一致.

由图 1可以看出，长白山阔叶红松林生态系统 NEP积累于生长季的最旺盛时期，其中，6—8月的碳积累量占全年总量的 90%以上，7月 NEP最高，达 1.23 $Mg C \cdot hm^{-2} \cdot month^{-1}$，主要原因是该时期水、热配合充分，有利于树木生长，虽然此时的呼吸速率是一年中最高，但生长速率远大于呼吸速率，该时期的长白山阔叶红松林是碳“汇”.

4月，研究区总初级生产力 (GPP)为 0.1 $Mg C \cdot hm^{-2} \cdot month^{-1}$，这是由于针叶树在气温高于 0℃就有一定的光合作用所致[42]. 研究区 7月 GPP最大 (5.62 $Mg C \cdot hm^{-2} \cdot month^{-1}$)，然后依次为 8月 (3.11 $Mg C \cdot hm^{-2} \cdot month^{-1}$)和 6月 (2.90 $Mg C \cdot hm^{-2} \cdot month^{-1}$)，而从 11月至翌年 3月，各月的 GPP均为 0，即这段时期树木没有进行光合作用.

长白山阔叶红松林生态系统 NPP的变化规律与 GPP基本相同. 该区 7月 NPP最大，为 3.53 $Mg C \cdot hm^{-2} \cdot month^{-1}$ (图 1). NPP为负是由于生态系统在非生长季节仍有一定的维持呼吸和土壤异养呼吸所致.

表 2 长白山阔叶红松林生态系统在现时及达到碳收支平衡时的碳动态模拟值

Tab. 2 Simulated values of carbon dynamics of broad-leaved Korean pine forest ecosystem at Changbai Mountains under present climate condition and at the equilibrium time of the present climate

项目 Item			单位 Unite	模拟数据 a) Simulated value	模拟数据 b) Simulated value
碳储量 Carbon storage (WE)	叶面积指数 Leaf area index (LAI)		—	4.7～5.5	5.5～6.9
	植被碳储量 Vegetation carbon stocks (WP)	叶碳储量 Leaf carbon storage (WP_F)	$Mg C \cdot hm^{-2}$	2.1	2.5
		枝干碳储量 Stem (branch) carbon storage (WP_C)	$Mg C \cdot hm^{-2}$	120.9	153.5
		根碳储量 Root carbon storage (WP_R)	$Mg C \cdot hm^{-2}$	23.9	27.8
	土壤碳储量 Soil carbon storages (WS)	凋落物碳储量 Litter soil carbon storage (WS_L)	$Mg C \cdot hm^{-2}$	7.6	8.7
		矿质土壤碳储量 Mineral soil carbon storage (WS_H)	$Mg C \cdot hm^{-2}$	287.8	358.3
碳通量 Carbon effluxes	植被生产力 Vegetation productivity	总初级生产力 Gross primary productivity (GPP)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	14.9	17.7
		净初级生产力 Net primary productivity (NPP)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	8.7	7.3
		生态系统净生产力 Net ecosystem productivity (NEP)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	2.7	0
		NPP/GPP	—	0.58	0.42
	呼吸 Respiration	植物呼吸量 Autotrophic respiration (AR)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	6.2	10.4
		土壤异养呼吸量 Heterotrophic respiration (HR)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	6.7	7.3
其他参数 Other parameter		干物质生产效率 Efficiency of dry matter production (WP/NPP)	a	16.9	25.2
		干物质生产水分利用效率 Water use efficiency of dry matter production (WUE)	$g C \cdot kg^{-1} H_2O$	1.58	1.66
		土壤周转率 Soil return rate (WS/NPP)	a	32.8	51.5
		凋落物量 Litter quantity (LF)	$Mg C \cdot hm^{-2} \cdot a^{-1}$	3.6	4.3
		根冠比 Ratio of root and shoots	%	19.4	17.8

a) 现时长白山阔叶红松林参数的模拟值 The simulation on the broad-leaved Korean pine forest under present climate condition; b) 碳平衡时长白山阔叶红松林参数模拟值 The simulation on the broad-leaved Korean pine forest at the equilibrium time under present climate condition.

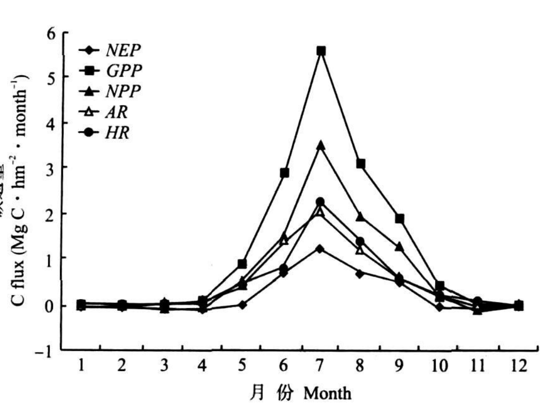

图 1 现时研究区碳通量的季节动态模拟

Fig. 1 Simulation of seasonal dynamics of carbon fluxes in the study area at the present

NEP: 生态系统净生产力 Net ecosystem productivity; GPP: 总初级生产力 Gross primary productivity; NPP: 净初级生产力 Net primary productivity; AR: 植物呼吸量 Autotrophic respiration; HR: 土壤异养呼吸量 Heterotrophic respiration. 下同 The same below.

在研究区非生长季节(11月到翌年 3月),长白山阔叶红松林生态系统的植物呼吸量(AR)和土壤异养呼吸量(HR)为 0.04～0.18 $Mg C \cdot hm^{-2} \cdot month^{-1}$,其中,4月最高,为 0.18 $Mg C \cdot hm^{-2} \cdot month^{-1}$,1月和 2月最低,均为 0.04 $Mg C \cdot hm^{-2} \cdot month^{-1}$. AR和 HR与温度呈密切正相关关系[24],由于气温下降早于土壤温度,因此长白山阔叶红松林生态系统 AR下降的开始期早于 HR,且前者的降幅大于后者.

长白山阔叶红松林生态系统的年 GPP为 14.9 $Mg C \cdot hm^{-2}$,该结果与 Zhang等[22]用涡度相关法测定的范围(12.16～14.89 $Mg C \cdot hm^{-2} \cdot a^{-1}$)一致;研究区年 NPP和 NEP分别为 8.22 $Mg C \cdot hm^{-2}$ 和 2.67 $Mg C \cdot hm^{-2}$,其与涡度相关法的测定结果基本一致[20].长白山阔叶红松林生态系统总呼吸量为 12.62 $Mg C \cdot hm^{-2} \cdot a^{-1}$,其中,HR为 7.25 $Mg C \cdot hm^{-2} \cdot a^{-1}$,这与静态箱/气相色谱法的 HR实测值(6.21 $Mg C \cdot hm^{-2} \cdot a^{-1}$)[43]基本一致.

2.1.2 生态系统碳收支平衡时的碳动态模拟 在当

前气候情景下，长白山阔叶红松林生态系统需 498 a 才能达到碳收支的动态平衡[24]. 达到碳动态平衡时，长白山阔叶红松林生态系统碳储量 (WE)为 550.8 Mg C・hm^{-2}，其中，WP和 WS分别为 183.8 和 367.0 Mg C・hm^{-2}，两者分别占整个生态系统碳储量的 33.4%和 66.6% (表 2). 在植被碳储量中，枝干、叶和根的碳储量分别为 153.5、2.5和 27.8 Mg C・hm^{-2}，分别占植物总碳储量的 83.5%、1.3%和 15.2%；凋落物和矿质土壤碳储量分别为 8.7和 358.3 Mg C・hm^{-2}. 此时，研究区 LAI在 5.5～6.9，大于现时 LAI模拟值，表明长白山阔叶红松林生态系统的碳收支平衡过程是叶面积指数不断增加的过程.

现时长白山阔叶红松林 GPP模拟值比碳收支平衡时的 GPP模拟值小 2.9 Mg C・hm^{-2}・a^{-1}，但现时 NPP模拟值 (8.7 Mg C・hm^{-2}・a^{-1})却大于碳收支平衡时的 NPP模拟值 (7.3 Mg C・hm^{-2}・a^{-1})，表明从现在到碳平衡的过程是长白山阔叶红松林生态系统 NPP逐渐降低的过程. 碳收支平衡时长白山阔叶红松林干物质生产效率的模拟值为 0.42，低于现时干物质生产效率的模拟值 (0.58)，说明从现时到碳平衡的过程是长白山阔叶红松林生态系统干物质生产效率逐渐降低的过程. 当生态系统干物质生产效率为 0.42时，碳积累速率接近 0，即碳收支达到动态的平衡状态. 碳平衡时研究区土壤周转率为 37.7 a，比现时土壤周转率模拟值多 3.1 a，说明长白山阔叶红松林生态系统土壤周转率的变化呈缓慢而增加的趋势. 其原因可能是从现时到碳平衡的过程中，土壤碳储量增加量大于生态系统其他组分碳储量增加的数量，进而延长了有机物质的分解时间.

由图 2可以看出，长白山阔叶红松林生态系统碳动态平衡时 NEP、GPP和 NPP的年动态规律同现时长白山阔叶红松林的 NEP、GPP和 NPP动态变化规律相同. 碳平衡时长白山阔叶红松林生长季各月 GPP模拟值均大于现时生态系统的 GPP模拟值；而碳平衡时长白山阔叶红松林非生长季各月 NPP模拟值大于现时 NPP模拟值，生长季各月 NPP模拟值小于现时 NPP模拟值. 长白山阔叶红松林生态系统碳平衡时的植物呼吸量 (AR)和土壤异养呼吸量 (HR)的动态规律与现时长白山阔叶红松林生态系统的动态规律相同，但它们均大于现时的阔叶红松林的模拟值.

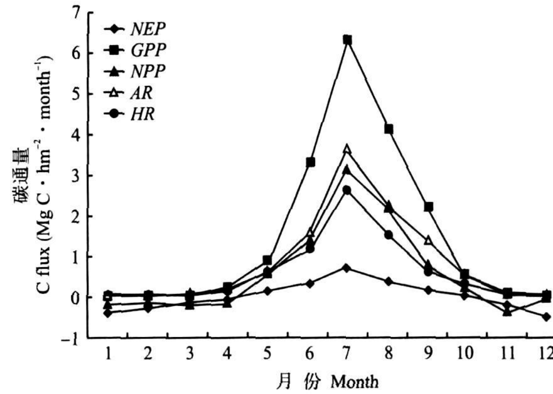

图 2 碳平衡时研究区碳通量的季节动态模拟

Fig. 2 Simulation of seasonal dynamics of carbon fluxes in the study area at the equilibrium of carbon cycles

2.2 气候变化情景下长白山阔叶红松林生态系统的碳动态模拟

大气环流模型对未来全球变化的预测结果[44-45]表明，气候变化主要是温度增加[14]和 CO_2 浓度增加[32]. 本研究考虑 3种未来全球气候变化情景：1)单纯温度增加 (C_0T_2)，即温度增加 2℃、CO_2 浓度不变；2)单纯 CO_2 浓度倍增、温度不变 (C_2T_0)，即 CO_2 浓度在未来 50 a间从 360 μmol・mol^{-1}增加到 720 μmol・mol^{-1}期间温度不发生变化；3) CO_2 浓度倍增、温度增加 (C_2T_2)，即温度增加 2℃、CO_2 浓度未来 50 a间从 360 μmol・mol^{-1}增加到 720 μmol・mol^{-1}.

由表 3可以看出，在 C_0T_2 情景下，长白山阔叶红松林 WS为 (303.9±18.0) Mg C・hm^{-2}，比气候不变情况增加了 (3.2±0.5) Mg C・hm^{-2}；WP增加

表 3　长白山阔叶红松林生态系统对气候变化的响应

Tab. 3　Response to climate change of broad-leaved Korean pine forest ecosystem at Changbai Mountains (mean±SD)

项 目 Item		气候情景 Climate scenario C_0T_2	C_2T_0	C_2T_2
WP	WP_F	2.3±0.3	2.5±0.5	2.6±0.6
	WP_C	128.1±3.1	135.4±5.2	139.4±5.6
	WP_R	26.1±2.1	26.8±2.0	27.0±2.3
WS	WS_L	8.1±1.0	8.2±1.1	8.2±0.9
	WS_H	295.8±16.7	304.9±19.1	309.5±20.7
植被生产力	GPP	15.2±2.1	17.9±1.7	18.0±1.9
Plant	NPP	8.5±1.6	8.8±1.8	9.0±1.5
productivity	NEP	2.5±0.5	2.8±0.6	2.9±0.7
	NPP/GPP	0.56	0.55	0.55
呼 吸	AR	7.1±0.9	6.8±1.0	7.1±1.2
Respiration	HR	7.0±0.8	6.9±0.7	7.0±0.9

T_0：温度不变 No change in temperature　T_2：温度增加 2℃ Temperature with 2℃ increment　C_0：CO_2 浓度不变 No change in CO_2 concentration　C_2：CO_2 浓度倍增 Doubling CO_2 concentration.

了(0.5±0.1) Mg C·hm^{-2};NPP模拟值为(8.8±1.4) Mg C·hm^{-2}·a^{-1},NEP模拟值为(2.6±0.6) Mg C·hm^{-2}·a^{-1}.

在 C_2T_0 情景下,长白山阔叶红松林生态系统WS为(313.1±21.1) Mg C·hm^{-2}, WP为(164.5±8.5) Mg C·hm^{-2},两者分别比气候不变情景增加了 23.75和 26.31 Mg C·hm^{-2};NPP模拟值增加了 1.13 Mg C·hm^{-2}·a^{-1}.这是由于 CO_2 浓度增加使光合作用增强,导致生态系统第一性生产力随之增大;同时,森林生态系统叶面积指数的增加也增强了光合产物的积累,增加了森林净生态系统生产力,提高了碳储量.然而 NPP模拟值的增幅小于 OTC和 FACE等 CO_2 倍增试验得到的数据,说明 CO_2 倍增试验过高地估计了 CO_2 的施肥效应[14].

在 C_2T_2 情景持续 50 a的条件下,长白山阔叶红松林生态系统 WS由(292.9±18.6) Mg C·hm^{-2} 增加到(309.5±20.7) Mg C·hm^{-2},WP从(151.2±4.5) Mg C·hm^{-2}增至(172.4±9.7) Mg C·hm^{-2}. NPP模拟值为(9.0±1.5) Mg C·hm^{-2}·a^{-1},NEP模拟值为(2.9±0.5) Mg C·hm^{-2}·a^{-1}.

3 结 语

本文利用 Sim-CYCLE模型模拟和分析了长白山阔叶红松林生态系统在当前和气候变化情景时碳储量和碳通量的变化.结果表明,该模型可合理解释长白山阔叶红松林生态系统碳储量和碳通量的动态机理;且模拟的碳储量和 NPP值与实际观测资料均达到较高的一致性.长白山阔叶红松林生态系统是碳“汇”,这与许多研究结果一致[16-17,20,22].长白山阔叶红松林生态系统 6—8月的 NEP占全年总量的90%以上;4月 GPP模拟值为 0.1 Mg C·hm^{-2}·$month^{-1}$,这可能是由于针叶树种在气温高于 0℃就有一定光合作用所致.

在 CO_2 浓度倍增、温度不变的气候情景时,长白山阔叶红松林生态系统 NPP模拟值比现时 NPP模拟值增加了 20%左右,仅略高于方精云[46]的模拟结果,其原因可能是由于本研究中 CO_2 浓度倍增为 720 μmol·mol^{-1},而方精云[46]设定的 CO_2 浓度倍增为 625 μmol·mol^{-1}.在温度增加 2℃、CO_2 浓度倍增的气候情景时,研究区 NPP达 21%左右,远低于方精云[46]的模拟结果,这可能是由于方精云[46]在模拟时增加了 20%降水量的缘故.气温增加延长了生长季,提高光合效率和植物生产力,提高了生态系统的生产力和碳储量. CO_2 浓度增加在短期内可促进树木的光合速率、降低气孔导度、提高水分利用效率,从而提高生产力,然而长期处于高 CO_2 浓度下,树木光合速率会逐渐恢复到原有水平[44,47-49]. CO_2 浓度增加和温度增加对植被第一性生产力的影响较复杂,两者的耦合作用对植被第一性生产力和碳储量的影响并不是单一影响的相加,还有待深入研究.

致谢 辽宁大学计算中心白永臣副教授和辽宁大学数学学院李铁博士在模型运算过程中给予大力帮助,谨致谢忱.

参考文献

[1] Bazzaz FA. Plants in Changing Environment: Linking Physiological Population and Community Ecology. Cambridge: Cambridge University Press, 1996

[2] Intergovernmental Panel on Climate Change (IPCC). Climate Change 1995: The Science of Climate Change. Cambridge: Cambridge University Press, 1996

[3] Ito A, Oikawa T. The large carbon emission from terrestrial ecosystems in 1998: A model simulation. Journal of the Meteorological Society of Japan, 2000, **78**: 103–110

[4] Keeling CD, Bacastow RB, Carter AF, et al. A three-dimensional model of atmospheric CO_2 transport based on observed winds Ⅰ. Analysis of observational data. Geophysical Monography, 1989, **55**: 165–236

[5] Fan SM, Blaine TL, Sarmiento JL. Terrestrial carbon sink in the Northern Hemisphere estimated from the atmospheric CO_2 difference between Mauna Loa and the South Pole since 1959. Tellus Series B: Chemical and Physical Meteorology, 1999, **51**: 863–870

[6] Houghton RA, Davidson EA, Woodwell GM. Missing sinks, feedbacks and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochemical Cycles, 1998, **12**: 25–34

[7] Cao MK, Woodward FI. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. Global Change Biology, 1998, **4**: 185–198

[8] Raich JW, Rastetter EB, Melillo JM, et al. Potential net primary productivity in South America: Application of a global model. Ecological Application, 1991, **1**: 399–429

[9] Ruimy A, Dedieu G, Saugier B, et al. A diagnostic model of continental gross primary productivity and net primary productivity. Global Biogeochemical Cycles, 1996, **10**: 269–285

[10] Friend AD, Stevens AK, Knox RG, et al. A process-

based terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). Ecological Modelling, 1997, **95**: 249—287

[11] McMuitrie RE, Comins HN, Kirschbaum MUF, et al. Modifying existing forest growth models to take account of effects of elevated CO_2. Australian Journal of Botany, 1992, **40**: 657—677

[12] Rasse DP, Francois L, Aubinet M, et al. Modelling short-term CO_2 fluxes and long-term tree growth in temperate forests with ASPECTS. Ecological Modelling, 2001, **141**: 35—52

[13] Zhou G-S (周广胜), Wang Y-H (王玉辉), Jiang Y-L (蒋延玲). Global change and water-driven IGBP-NECT, Northeast China. Earth Science Frontiers (地学前缘), 2002, **9**(1): 198—216 (in Chinese)

[14] Cheng X-X (程肖侠), Yan X-D (延晓冬). Effects of climate change on typical forest in the northeast of China. Acta Ecologica Sinica (生态学报), 2008, **28**(2): 534—543 (in Chinese)

[15] Wang P-J (王培娟), Xie D-H (谢东辉), Zhang J-H (张佳华), et al. Spatial scaling of net primary productivity based on process model in Changbai Mountain Natural Reserve. Acta Ecologica Sinica (生态学报), 2007, **27**(8): 3215—3233 (in Chinese)

[16] Yan X-D (延晓冬), Zhao J-F (赵俊芳). Establishing and validation individual-based carbon budget model FORCCHN of forest ecosystems in China. Acta Ecologica Sinica (生态学报), 2007, **27**(7): 2684—2694 (in Chinese)

[17] Zhao J-F (赵俊芳), Yan X-D (延晓冬), Jia G-S (贾根锁). Simulating the response of forest net primary productivity and carbon budget to climate change in Northeast China. Acta Ecologica Sinica (生态学报), 2008, **28**(1): 92—102 (in Chinese)

[18] Yan X-D (延晓冬), Zhao S-D (赵士洞). Simulation model of carbon storage dynamics in temperate broad-leaved-coniferous mixed forest ecosystem. I. Dynamics of carbon storage in tree layer. Chinese Journal of Ecology (生态学杂志), 1995, **14**(2): 6—13 (in Chinese)

[19] Guan D-X (关德新), Wu J-B (吴家兵), Jin C-J (金昌杰), et al. Diurnal and seasonal variation of CO_2 flux above the Korean pine and broad-leaved mixed forest in Changbai Mountain. Scientia Silvae Sinicae (林业科学), 2006, **42**(10): 123—128 (in Chinese)

[20] Ren C-Y (任传友), Yu G-R (于贵瑞), Wang Q-F (王秋凤), et al. A coupled model of photosynthesis-transpiration of an ecosystem in the canopy scale. Chinese Sciences Series D (中国科学 D辑), 2004, **34** (Suppl.2): 141—151 (in Chinese)

[21] Wu J-B (吴家兵), Guan D-X (关德新), Zhang M (张弥), et al. Carbon budget characteristics of the broadleaved Korean pine forests in Changbai Mountain. Journal of Beijing Forestry University (北京林业大学学报), 2007, **29**(1): 1—6 (in Chinese)

[22] Zhang JH, Han SJ, Yu GR. Seasonal variation in carbon dioxide exchange over a 200-year-old Chinese broad-leaved Korean pine mixed forest. Agricultural and Forest Meteorology, 2006, **137**: 150—165

[23] Wang Z (王战), Xu Z-B (徐振帮), Li X (李昕), et al. The main forest types and their features of community structure in northern slope of Changbai Mountain. Research of Forest Ecosystems (森林生态系统研究), 1980, **1**: 25—43 (in Chinese)

[24] Oikawa T. Simulation of forest carbon dynamics based on a dry-matter production model. I. Fundamental model structure of a tropical rainforest ecosystem. Botanical Magazine, 1985, **98**: 225—238

[25] Oikawa T. Simulation of forest carbon dynamics based on a dry-matter production model. III. Effects of increasing CO_2 upon a tropical rainforest ecosystem. Botanical Magazine, 1986, **99**: 419—430

[26] Oikawa T. Modeling carbon dynamics of a lucidophyll forest under monsoon climates. Global Environmental Research, 1998, **1**: 25—33

[27] Oikawa T. Comparison of ecological characteristics between forest and grassland ecosystems based on a dry-matter production model. Journal of Environmental Science, 1993, **7**: 67—78

[28] Ito A. Modeling of carbon cycle and fire regime in an east Siberian larch forest. Ecological Modelling, 2005, **187**: 121—139

[29] Ito A, Saigusa N, Murayama S, et al. Modeling of gross and net carbon dioxide exchange over cool-temperature deciduous broad-leaved forest in Japan: Analysis of seasonal and interannual change. Agricultural and Forest Meteorology, 2005, **134**: 122—134

[30] Ito A. The regional carbon budget of East Asia simulated with a terrestrial ecosystem model and validated using AsiaFlux data. Agricultural and Forest Meteorology, 2008, **148**: 738—747

[31] Alexandrov GA, Oikawa T. Net ecosystem production resulted from CO_2 enrichment: Evaluation of potential response of a Savannah ecosystem to global changes in atmospheric composition. Proceedings of the Tsukuba Global Carbon Cycle Workshop — Global Environment Tsukuba '95, Tsukuba, 1995: 161—168

[32] Prentice JC, Farquhar GD. The carbon cycle and atmosphere CO_2 // Houghton JH, Yihui D, eds. The Intergovernmental Panel on Climate Change (IPCC). Cam-

bridge: Cambridge University Press, 2001

[33] Xu Z-B (徐振帮). Study on the distribution of root system of main tree species on broad-leaved Korean pine mixed forest at Changbai Mountain. Chinese Journal of Ecology (生态学杂志), 1987, **6**(4): 19–24 (in Chinese)

[34] Yan X-D (延晓冬), Zhao S-D (赵士洞). Modeling growth and succession of the forest ecosystem of Changbai Mountain. Acta Ecologica Sinica (生态学报), 1996, **16**(1): 12–21 (in Chinese)

[35] Pei T-F (裴铁璠), Li J-Z (李建志), Li X-Y (李晓宴), et al. Mathematic model on infiltration coefficient of forest soil. Research of Forest Ecosystems (森林生态系统研究), 1981, **2**: 187–195 (in Chinese)

[36] Li W-H (李文华), Deng K-M (邓坤枚), Li F (李飞). Study on the biomass and yields of main forest ecosystems in Changbai Mountains. Research of Forest Ecosystems (森林生态系统研究), 1981, **2**: 34–50 (in Chinese)

[37] Fang JY, Chen AP, Peng CH, et al. Changes in forest biomass carbon storage in China between 1949 and 1998. Science, 2001, **292**: 2320–2323

[38] Cheng B-R (程伯荣), Xu G-S (许广山), Lu F-Y (卢凤永), et al. The main soil groups and their properties of the natural reserve on northern slop of Changbai Mountain. Research of Forest Ecosystems (森林生态系统研究), 1981, **2**: 196–206 (in Chinese)

[39] Zhang N (张 娜), Yu G-R (于贵瑞), Yu Z-L (于振良), et al. Simulation of temporal-spatial variation characteristics of surface runoff in Changbai Mountain based on process model for landscape scale. Chinese Journal of Applied Ecology (应用生态学报), 2003, **14**(5): 653–658 (in Chinese)

[40] Guan D-X (关德新), Wu J-B (吴家兵), Wang A-Z (王安志), et al. Simulation of crown leaf area index of Korean pine and broadleaved mixed forest in Changbai Mountains. Chinese Journal of Applied Ecology (应用生态学报), 2007, **18**(3): 499–503 (in Chinese)

[41] Shao Y-H (邵月红), Pan J-J (潘剑君), Xu X-W (许信旺), et al. Determination of soil organic carbon pool sizes and turnover rates in Changbai Mountains. Journal of Soil and Water Conservation (水土保持学报), 2006, **20**(6): 99–102 (in Chinese)

[42] Monsi M. Dry-matter reproduction in plants. I. Schemata of dry-matter reproduction. Botanical Magazine, 1960, **73**: 81–90

[43] Lin L-S (林丽莎), Han S-J (韩士杰), Wang Y-S (王跃思). The soil CO_2 efflux in broad-leaved Korean pine forests of Changbai Mountain. Journal of Northeast Forestry University (东北林业大学学报), 2005, **33**(1): 11–13 (in Chinese)

[44] Liu G-H (刘国华), Fu B-J (傅伯杰). Response of forest ecosystem to global warming change. Journal of Natural Resources (自然资源学报), 2001, **16**(1): 71–78 (in Chinese)

[45] Shackley S, Young P, Parkinson S, et al. Uncertainty, complexity and concepts of good science in climate change modelling: Are GCMs the best tools? Climatic Change, 1998, **38**: 159–205

[46] Fang J-Y (方精云). Forest productivity in China and its response to global climate change. Acta Phytoecologica Sinica (植物生态学报), 2000, **24**(5): 513–517 (in Chinese)

[47] Meier M, Fuhrer J. Effect of elevated CO_2 on orchard grass and red clover grown in mixture at two level of nitrogen or water supply. Environmental and Experimental Botany, 1997, **38**: 251–262

[48] Wang Y (王 叶), Yan X-D (延晓冬). The response of the forest ecosysten in China to global climate change. Chinese Journal of Atmospheric Sciences (大气科学), 2006, **30**(5): 10–15 (in Chinese)

[49] Zhe G-S (周广胜), Wang Y-H (王玉辉), Bai L-P (白莉萍), et al. Study on the interaction between terrestrial ecosystems and global change. Acta Meteorologica Sinica (气象学报), 2004, **62**(5): 14–19 (in Chinese)

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