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气候变化背景下紫丁香花期物候特征及其模拟研究

李荣平,张晓月,李 晶

(辽宁省气象科学研究所,辽宁 沈阳 110166)

摘 要:紫丁香开花时间和花期长短的精准模拟对于避开花期过敏和开展赏花旅游具有重要意义。该试验采用模拟退火算法积温模型对开花期模拟的适用性,并基于统计原理探讨了紫丁香不同开花期的积温指标及其与气温的关系,建立了紫丁香开花末期的新模拟模型。结果表明:紫丁香开花始期和开花盛期>5 ℃积温具有较好的稳定性,能够利用积温模型进行模拟。紫丁香开花末期>5 ℃积温波动较大,与5月平均气温呈显著正相关,气温的升高导致紫丁花的花期延长。紫丁香开花始期和开花末期的利用积温模型模拟,最高解释率分别为45.1%和26.2%,而紫丁香开花末期通过>5 ℃积温与花期的平均气温的线性拟合方程和积温方程组合,模型解释率达80.0%,明显提高模型的模拟精度。

关键词:紫丁香;开花;物候模型;积温

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植物的形态特征随季节变化而发生显著改变,植物的展叶、开花、落叶等过程随气候变化也发生显著变化,同一时间,不同地点和相同地点不同时间,同一种植物物候期会发生波动,对于这种波动的精确把握对区域碳收支精确评估、区域气候模式的改进和提高具有重要意义[1],同时对于花期旅游和花粉酿蜜具有重要指导意义。

黑龙江地处中国东北,地形复杂,季风气候明

第一作者简介:李荣平(1975-),男,江西新建人,博士,副研究员,现主要从事农业气象等研究工作。E-mail:rongpingli@aliyun.com.

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seedlings, the content of pigment (chlorophyll a, chlorophyll b and carotenoid content was decreased) was generally lower than that of the control. Chlorophyll a, b and carrots in the process of pure Pb tailing liquid condition made the content of carotene was decreased by 14.6% than CK, 29.6% and 23.2%. The underground and aboveground of seedling *Myriophyllum* relative conductivity and Pb tailing liquid were proportional to the concentration of which was higher than the control. With the increasing of the concentration of Pb tailings, the treatment of the aboveground and underground part of proline (Pro) content was showed the overall upward trend. The aboveground and underground parts (AsA) and the content of glutathione (GSH) changes were showed low concentration and high concentration decreased. In the 75% NH and 25% Pb stress condition, the content of AsA in the aboveground and underground parts of *Myriophyllum*′s seedlings were the highest, compared with the control group significantly ($P<0.05$), increased 93.5% and 89.8%. However, the aboveground and underground parts of GSH′s content increased by 35.7% and 4.36%. The experimental data showed that spicatum could be used for ecological restoration of Pb contaminated environment as long as Pb stressed environment to a certain degree.

Keywords: *Myriophyllum verticillatum* Linn.; Pb tailing liquid; tolerance; repair

显,已有研究表明,过去的几十年,该地区气候变暖明显,并已经显著的影响着该地区植被的生长发育[2],一些学者对该地区植物物候开展了大量研究[3],并得出气候变暖导致春季物候提前,秋季物候推后的结论[4]。但是有关花期预报的研究较少。紫丁香属木犀科落叶灌木或小乔木,在黑龙江广泛分布,属于气传致敏植物[5],同时具有较强的观赏价值。随着人们健康意识的不断提高,花粉致敏被日益重视,同时随着人们生活水平提高,赏花旅游也日益受到关注,因此,紫丁香花期特征和预测能为花粉过敏者和赏花旅游业提供精确的信息服务。

1 材料与方法

紫丁香花期物候数据来源于黑龙江 13 个农业气象试验站,时间范围为 1986—2004 年(表 1),气温数据采用与之相配的站点气象观测数据。利用哈尔滨和佳木斯的紫丁香开花始期和末期数据和气温数据,采用模拟退火算法计算积温的参数,利用所有数据进行模型验证。积温模型:$T_{sum}=T_i-T_b(T_i>T_b)$,其中,T_b:基础温度(℃),T_{sum}:积温阈值(℃·d),T_i:日平均气温(℃)。改进的积温模型:$T_{sum5}=A\times T_5+B$,$T_{sum5}=T_i-5\ (T_i>5)$。式中:T_{sum5}:>5 ℃的积温阈值(℃·d);A、B:系数;T_5:5 月平均气温(℃)。$T(i)$:日平均气温(℃)。

模型精度验证,采用均方根误差、绝对值误差和解释率等指标来比较。

$$均方根误差(RMSE)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-O_i)^2},$$

$$绝对值误差(AE)=\frac{1}{n}\sum_{i=1}^{n}|P_i-O_i|,$$

$$解释率(R^2)=1-\frac{\sum(P_i-O_i)^2}{\sum(O_i-\bar{O})^2}。$$

2 结果与分析

2.1 紫丁香花期物候特征

黑龙江紫丁香开花始期在 5 月上中旬,开花盛期在 5 月中旬后半段,开花末期在 5 月下旬(表 1),开花始期和开花盛期的>5 ℃积温平均值分别为 144.82 ℃·d 和 186.45 ℃·d,变异系数分别为 0.125 和 0.140,较为稳定;上述平均值和变异系数,开花末期分别为 270.62 ℃·d 和 0.214,较为不稳定(图 1)。

表 1 紫丁香花期物候观测地点、时间系列和各花期的平均日期

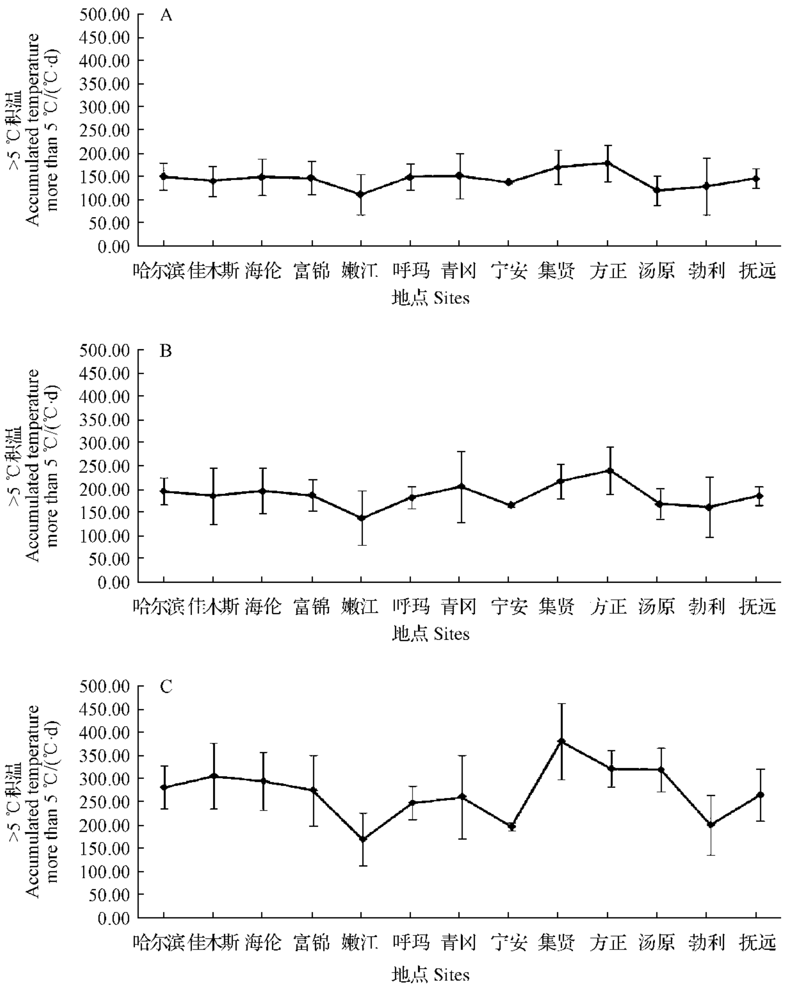
Table 1 Observation sites, time series and average dates of flowering phenology of lilacs 月-日

地点 Sites	年份 Year	始期 Initial stage	盛期 Peak stage	末期 Late stage	地点 Sites	年份 Year	始期 Initial stage	盛期 Peak stage	末期 Late stage
哈尔滨 Harbin	1990—2004	05-05	05-10	05-18	佳木斯 Jiamusi	1989—2003	05-07	05-12	05-24
海伦 Hailun	1987—2004	05-14	05-19	05-28	富锦 Fujin	1989—2004	05-12	05-16	05-24
嫩江 Nenjiang	1987—1997	05-14	05-17	05-20	呼玛 Huma	1990—2000	05-20	05-24	05-30
青冈 Qinggang	1986—2004	05-11	05-17	05-22	宁安 Ning'an	1991—1993	05-12	05-16	05-18
集贤 Jixian	1983—1991	05-10	05-16	05-30	方正 Fangzheng	1990—1997	05-16	05-23	05-30
汤原 Tangyuan	1990—2004	05-10	05-14	05-29	勃利 Boli	1988—2003	05-04	05-08	05-13
抚远 Fuyuan	1991—2004	05-13	05-17	05-26					

开花末期的>5 ℃积温与 5 月平均气温呈显著的正相关关系($R^2=0.690$),每增加 1 ℃,积温值增加 20.21 ℃·d(图 2),花期长短也与 5 月平均气温呈显著的正相关关系($R^2=0.350$),但不如积温与其相关关系明显。因此,尽管积温值波动较大,但可以通过 5 月平均气温的关系加以拟合,能够使之更为稳定。5 月的开花期一般认为是春季物候期,然而,与以往结论相反[6],气温升高,开花末期推后。

2.2 紫丁香花期物候模型参数

积温模型对紫丁香开花始期的最优解在基础温度为 3.015 2 ℃,积温阈值为 180.76 ℃·d 时出现,均方根误差为 4.23 d;开花末期的最优解发生在基础温度为 5.405 4 ℃,积温阈值为 260.16 ℃·d,均方根误差略大于开花始期,见表 2。



注：A. 开花始期；B. 开花盛期；C. 开花末期。

Note：A. Flowering initial stage；B. Flowering peak stage；C. Flowering late stage.

图1 黑龙江不同地方的紫丁香>5 ℃积温的变化特征

Fig. 1 Variation characteristics of accumulated temperature more than 5 ℃ of lilacs in different places of Heilongjiang

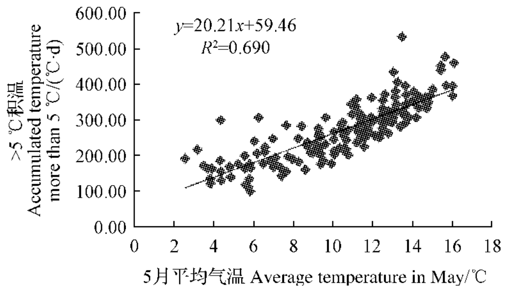


图2 黑龙江紫丁香开花末期>5 ℃积温与5月平均气温的关系

Fig. 2 Relationship between the accumulated temperature more than 5 ℃ at the end of flowering period and the average temperature in May in Heilongjiang

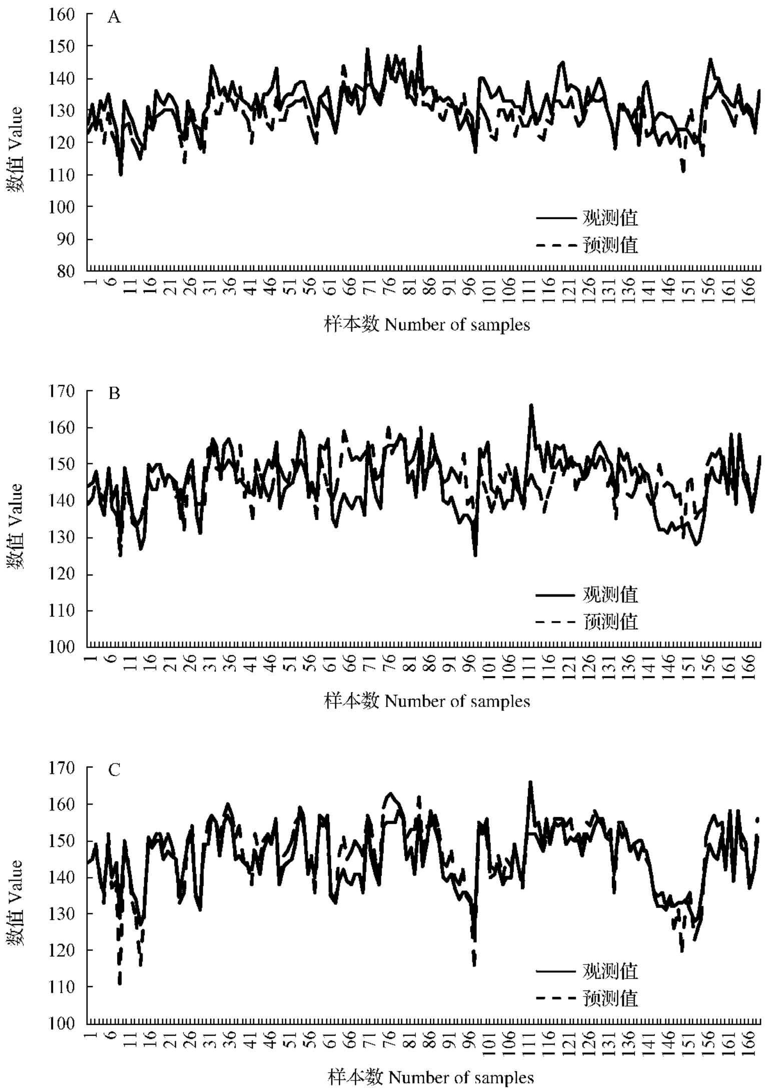
2.3 紫丁香开花始期和末期预测

采用最优解参数，利用气温数据，采用积温模型预报开花始期和开花末期，模型的解释率分别为45.1%和26.2%，绝对值误差分别为5.06、5.89 d，均方根误差分别为6.22、7.22 d(图3A，B)，耦合了5月平均气温，能够更好的模拟开花末期，解释率为80%，绝对值误差为3.48 d，均方根误差为4.58 d(图3C)。云文丽等[6]利用统计学方法对呼和浩特紫丁香盛花期建立预报模型，仅仅阐述了某几年得到较好的模拟结果，同时规避了模型解释率，而利用积温模型，通过对不同时间，不同地点的验证，对于始花期能够得到一定的

表 2 积温模型对紫丁香开花始期和开花末期的参数

Table 2 Parameters of the accumulated temperature model on the beginning and end of flowering of lilacs

开花始期 Flowering initial stage			开花末期 Flowering late stage		
基础温度 T_b/℃	积温阈值 Tsum/(℃·d)	均方根误差 RMSE/d	基础温度 T_b/℃	积温阈值 Tsum/(℃·d)	均方根误差 RMSE/d
8.276 8	68.38	4.53	9.917 3	99.34	4.81
5.635 6	114.38	4.36	7.017 0	203.90	4.80
5.219 7	125.18	4.27	6.276 9	230.59	4.77
3.783 4	161.52	4.23	6.086 7	233.59	4.72
2.907 8	182.70	4.23	6.036 5	236.29	4.70
3.015 2	180.76	4.23	5.405 4	260.16	4.70



注:A. 开花始期的积温模型;B. 开花末期的积温模型;C. 开花末期的改进型积温模型。

Note:A. Accumulated temperature model of flowering initial stage; B. Accumulated temperature model of flowering late stage; C. Improved accumulated temperature model of flowering late stage.

图 3 不同模型对紫丁香开花始期和开花末期的模拟

Fig. 3 Simulation of initial and late flowering stage of lilacs by different models

解释率，但是对于开花末期解释能力较差，当考虑花期温度对花期积温数量的影响，能够达到理想的模拟精度。

3 结论

紫丁香开花始期和开花盛期的>5 ℃积温具有较好的稳定性，平均值分别为144.82 ℃·d和186.45 ℃·d，能够利用积温模型进行模拟。紫丁香开花末期的>5 ℃积温波动较大，但是，积温值与开花期平均气温呈显著的正相关关系，黑龙江紫丁香开花末期的>5 ℃积温受5月平均气温影响，气温的升高导致紫丁花的花期延长。紫丁香开花始期和开花末期的最佳基础温度分别为3.02 ℃和5.41 ℃，对应的积温阈值分别为180.76 ℃·d和260.16 ℃·d，利用该参数的积温模型模拟紫丁香开花始期和开花末期，解释率分别为45.1%和26.2%，而紫丁香开花末期通过>5 ℃积温与花期的平均气温的线性拟合方程和积温方程组合，模型解释率达80.0%，明显提高模型的模拟精度。

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Flowering Phenology Characteristics and Simulation of Lilacs Under Climate Change

LI Rongping, ZHANG Xiaoyue, LI Jing

(Liaoning Institute of Meteorological Science, Shenyang, Liaoning 110166)

Abstract: Accurate simulation of flowering and flowering time length of lilacs has important significance for avoid allergies and blooming flowers tourism. The applicability of the accumulated temperature model to lilacs flowering period was tested by using the simulated annealing algorithm. At the same time, the principle of statistical index of the accumulated temperature of lilacs different flowering period and its relationship with the temperature were discussed. The new simulation model for the end of lilacs bloom was established. The results showed that accumulated temperature with beyond 5 ℃ in the begin and mid of lilacs bloom had good stability, which were simulated using the accumulated temperature model. Accumulated temperature with beyond 5 ℃ in the end of lilacs bloom had big fluctuation, it had significantly positively relationship with average temperature in May, temperatures raise resulted in extend of lilac flowering stage. The begin and the end stage of lilacs bloom could be simulated well by accumulated temperature model, their highest explain rate was 45.1% and 26.2%, respectively. However, using accumulated temperature equation with 5 ℃ and the linear fitting equation of average temperature and accumulated temperature with 5 ℃, the end stage of lilacs bloom could be better simulated, the explain rate was 80.0%, significantly improved the simulation precision of the phenology.

Keywords: lilacs; flowering; phenology model; accumulated temperature