

基于田间空气中病菌孢子囊浓度的葡萄霜霉病病情估计模型研究

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摘要:【目的】明确沈阳地区空中病菌孢子囊浓度、气象因素(空气温度、相对湿度、降雨量和风速)对葡萄霜霉病田间病情发展的影响, 开展基于田间空气中孢子囊浓度的葡萄霜霉病病情预测模型研究。【方法】2016—2019年连续调查葡萄霜霉病田间病情, 对空气中病菌孢子囊浓度和气象因素进行定期监测, 经相关性分析和非线性回归分析, 构建并检验葡萄霜霉病病情预测模型。【结果】葡萄霜霉病季节流行曲线通常表现为S形曲线, 始发期为7月上旬至下旬, 盛发期为7月下旬至8月下旬, 衰退期为8月下旬至9月中下旬, 降雨量对葡萄霜霉病始发时间和流行程度具有重要影响。经相关性分析, 明确空气中孢子囊浓度主要与7 d平均相对湿度和7 d累积降雨量呈显著正相关($r>0.224, p<0.030$; $r>0.209, p<0.040$), 与日累积降雨量呈显著负相关($r>-0.233, p<0.025$), 确定上述3个气象因子是影响霜霉病菌孢子囊空气中飞散的主要气象因素。通过非线性回归分析, 明确了葡萄霜霉病田间病情与累积孢子囊浓度的关系均为幂函数关系, 其中病情指数与累积孢子囊浓度和一周前累积孢子囊浓度的拟合效果最佳。【结论】根据4 a田间小区试验结果, 可利用累积孢子囊浓度预测葡萄霜霉病田间病情发生程度。

关键词:葡萄霜霉病; 病情指数; 空气中孢子囊浓度; 气象因素; 预测模型

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Study on estimation model for grape downy mildew prediction based on airborne sporangium concentration of *Plasmopara viticola* in field

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Abstract:【Objective】Grape downy mildew is a typical airborne disease that can damage all green tissues on *Vitis* plants, including leaves, inflorescences, berries, tendrils and young canes. Sporangium is the important carrier of short distance transmission of the disease. The formation, maturation, germination and release of sporangium are affected by meteorological factors such as temperature, relative humidity, rainfall, illumination and wind speed. In order to clarify the effects of airborne sporangium concentration of *Plasmopara viticola* and meteorological factors (air temperature, relative humidity, rainfall and wind speed) on disease infection of grape downy mildew in Shenyang, a prediction model of grape downy mildew driven by airborne sporangium concentration of *P. viticola* was established to guide the effective control of the disease.【Methods】Shenyang, one of the production areas of table grapes in China, was chosen as the experimental base. Experiments were conducted during four growing seasons from 2016 to 2019. Four test plots were arranged from north to south, and the test cultivar was Centennial Seedless (*Vitis vinifera* L.), which was highly susceptible to grape downy mildew. Each experimental plot was 15 m long, and 5 m wide. Vine spacing was 0.5 m within rows and 0.6 m between rows. The plots were planted on April 30, 2016; April 28, 2017; May 5, 2018 and April 29, 2019. Each plot

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was irrigated and managed normally, and the cropping system was not treated with any fungicide in order to facilitate the onset of the disease epidemic. TRM-ZS1 meteorological ecological environment detector was installed in the orchard for regular recording meteorological data. The concentration of airborne sporangia of *P. viticola* was monitored daily with Burkard spore trap. The incidence and degree of grape downy mildew was investigated by using the five-point sampling method and 15 fixed grape seedlings were selected from each plot every seven days. Bivariate correlation method in SPSS 19.0 was used for correlation analysis, and Spearman correlation coefficient was used to obtain the correlation analysis results among disease index of grape downy mildew, airborne sporangium concentration of *P. viticola* and meteorological factors. Eight curve models were selected to fit the data of disease index and the accumulated sporangium concentration of *P. viticola* during 2016 to 2019. The coefficient of determination (R^2), *F* value (*F*), significance probability (*p*) and estimated standard deviation (Std E) were taken as the criteria of model selection to select the best prediction model for grape downy mildew. **【Results】** The disease progress curve of grape downy mildew was usually sigmoid, the exponential phase was from early July to late July, the logistic phase was from late July to late August, and the decline phase was from late August to mid-late September. Rainfall had an important effect on occurrence and prevalence of grape downy mildew. The variation curve of airborne sporangium concentration of *P. viticola* in the field showed a wavy change, which increased with the disease index in general. The airborne sporangium concentration decreased gradually as the disease stopped growing. In 2016, the date of first sporangia trapping in the field was June 20, and the airborne sporangium concentration increased slowly before July 1, then increased sharply, and reached the peak of 75 sporangium per m^3 on September 8. In 2017, the date of first sporangia trapping was June 26, the airborne sporangium concentration increased rapidly after July 11, and reached the maximum of 52 sporangium per m^3 on August 22. The date of first sporangia trapping was June 29, 2018, then the airborne sporangia concentration increased in a multi-peak curve, and reached the maximum of 57 sporangium per m^3 on September 8. The date of first sporangia trapping in the field in 2019 was June 26, the airborne sporangium concentration fluctuated at a low level before July 12, and reached the peak of 51 sporangium per m^3 on September 1. Correlation analysis showed that airborne sporangium concentration of *P. viticola* was significantly positively correlated with average relative humidity before 7 days ($r>0.224, p<0.030$) and accumulated rainfall before 7 days ($r>0.209, p<0.040$), but had a significant negative correlation with daily rainfall, indicating that the above three meteorological factors were the main meteorological factors affecting the airborne dispersion of *P. viticola*. There was no significant correlation between the sporangium concentration of *P. viticola* and the average daily air temperature, relative humidity and wind speed, indicating that the daily meteorological factors were not the key factors affecting the airborne dispersion of *P. viticola*. The relationship between disease index and the accumulated sporangium concentration was a power function by nonlinear regression analysis, and the best prediction model was based on the accumulated sporangium concentration before the day of disease measuring and the accumulated sporangium concentration before the current week of disease measuring. **【Conclusion】** Based on the analysis of 4-year plot experiment in the field, the accumulation of sporangium concentration of *P. viticola* can be used to predict disease progress of grape downy mildew in the field.

Key words: *Plasmopara viticola*; Disease index; Airborne sporangia concentration; Meteorological factors; Prediction model

由专性寄生菌葡萄单轴霉(*Plasmopara viticola*)引起的葡萄霜霉病(grape downy mildew)是一种典型的气传性病害,在世界各大葡萄产区均有发生,特别在雨水较多的年份严重流行^[1]。葡萄霜霉病属于多循环病害,具有病害潜育期短、病菌繁殖能力强、变异幅度大的特点。在环境条件适宜时,病菌在一个生长季内连续繁殖多代,导致病情呈暴发式发展^[2],给世界各地葡萄种植业和葡萄酒酿造业带来了严重威胁。

葡萄单轴霉的生活史包括有性繁殖(卵孢子)和无性繁殖(孢子囊)两个阶段^[3]。卵孢子在每年葡萄生育末期的病组织中形成,并随之于土壤中越冬,成为翌年霜霉病的主要初侵染源。成熟的卵孢子在潮湿的土壤或者水中萌发形成孢子囊,孢子囊随风雨散播到的葡萄绿色幼嫩组织上(叶片、嫩梢、花序、幼果等),由孢子囊萌发释放的游动孢子通过气孔或皮孔进入寄主组织,引起初侵染。病原菌的菌丝体在葡萄细胞间扩展和吸收营养,经过一定的潜育期后形成病斑,并产生孢子囊梗和孢子囊。孢子囊在适宜的气象条件下萌发产生游动孢子,进行反复再侵染,导致病害发生流行。在葡萄霜霉病的整个流行期,卵孢子和孢子囊的形成、成熟、萌发和释放等过程均受到气温、相对湿度、降雨、光照和风速等气象因素的影响^[4-6],其中我国学者发现空气中孢子囊浓度动态变化与气温、相对湿度、降雨和叶面湿润时数等气象因素密切相关,且田间病情扩展与空气中霜霉菌孢子囊浓度呈显著正相关^[7-9]。国内外学者发现,苹果白粉病和疮痂病、甘蓝黑斑病、小麦条锈病、小麦白粉病等许多植物病害病原菌孢子累积量的变化曲线常与病害发展曲线一致;同时利用二者之间的显著相关性,分别建立了基于不同时间段孢子累积量的病情估计回归模型,用以评估田间病情发生的严重程度^[10-16]。为此,笔者在本研究中于2016—2019年通过监测葡萄高感品种无核白鸡心试验小区病情指数、空气中孢子囊浓度及气象因素的变化动态,在分析田间空气中孢子囊浓度与气象因素的相关性基础上,探索葡萄霜霉病田间病情与不同时段的病菌孢子囊累积量的关系,建立基于田间空气中孢子囊浓度的葡萄霜霉病病情预估模型,为该病害的预测预报奠定前期基础和理论依据。

1 材料和方法

1.1 试验材料

供试葡萄品种为沈阳地区的主栽感病品种无核白鸡心。病菌孢子囊捕捉装置为Burkard定容式孢子捕捉器(Burkard公司,英国),气象数据采集装置为TRM-ZS1气象生态环境检测仪(锦州阳光科技发展有限公司,中国),孢子囊计数所用显微镜为奥林巴斯BX43生物显微镜(Olympus公司,日本)。

1.2 试验方法

1.2.1 试验地点及小区设计 试验地点安排在辽宁省农业科学院试验基地(41°49'34"N, 123°32'16"E)进行。葡萄霜霉病属于该园区常发病害。将试验区划分为4个小区,南北排列。每个小区长15 m,宽5 m,定植1年生苗木200株,行株距0.6 m×0.5 m,分别于2016年4月30日、2017年4月28日、2018年5月5日和2019年4月29日栽苗,移栽后常规栽培管理。小区边缘设置5行高抗霜霉病品种贝达一年生苗作为保护行,试验全程未进行任何化学药剂防治。

1.2.2 葡萄霜霉病病情调查方法 采用五点取样法,每小区选取固定的15株葡萄苗进行葡萄霜霉病调查。自田间自然发病后,每株随机选取2条枝蔓,每枝自下而上调查全部叶片,每7 d调查1次,直至9月下旬病情不再发展时结束,2016—2019年分别调查11、12、12和12次,详细记录葡萄苗的发病情况并计算病情指数。病情指数= $\sum (\text{各级病叶数} \times \text{相应级代表值}) / (\text{调查总叶数} \times \text{最高病级代表值}) \times 100$ 。葡萄霜霉病在叶片上的分级标准^[17]—0级:无病斑;1级:病斑面积占整个叶面积的5%以下;3级:占>5%~25%;5级:占>25%~50%;7级:占>50%~75%;9级:占75%以上。

1.2.3 空气中孢子囊捕捉及检测 每年于6月15日将孢子捕捉器安置于试验区的中心处,进气口距地面1.0 m。捕捉器内附着在鼓上的孢子捕捉带每周旋转一周,每周更换一次捕捉带。将黏附有孢子囊的捕捉带带回室内镜检。将捕捉带均匀剪成7段,每段48 mm,逐片置于显微镜下进行孢子囊计数统计。每段按捕捉鼓移动的方向抽样检查12次,所计量的3倍即为整条捕捉带上所有的孢子囊数量,根据捕捉器的进气速率计算出逐日的空气中孢子囊浓度(个·m⁻³)。

1.2.4 试验小区气象数据采集 采用TRM-ZS1气象生态环境检测仪每0.5 h采集1次空气温度、空气相对湿度、降雨量及风速等气象数据。气象站自动将采集到的空气温度、空气相对湿度和风速数据以日为单位,进行平均处理,得到日均气温、日均相对湿度和日均风速;将当日24 h之内的降雨量进行累计,得到日累积降雨量。

1.3 数据统计与分析

1.3.1 气象数据统计 将病情调查日前7 d的各项

气象数据(降雨量除外)进行平均,得到7 d平均气温、7 d平均相对湿度、7 d平均风速;将调查日前7 d降雨量进行累计,得到7 d累积降雨量。

1.3.2 空气中孢子囊浓度统计 累积孢子囊浓度(c_1)为病情调查日期前所有孢子囊的累积浓度;一周前累积孢子囊浓度(c_2)为病情调查当周前孢子囊的累积浓度;一旬前累积孢子囊浓度(c_3)为病情调查当周前孢子囊的累积浓度;当周累积孢子囊浓度(c_4)为病情调查当周内的孢子囊累积浓度(图1)。

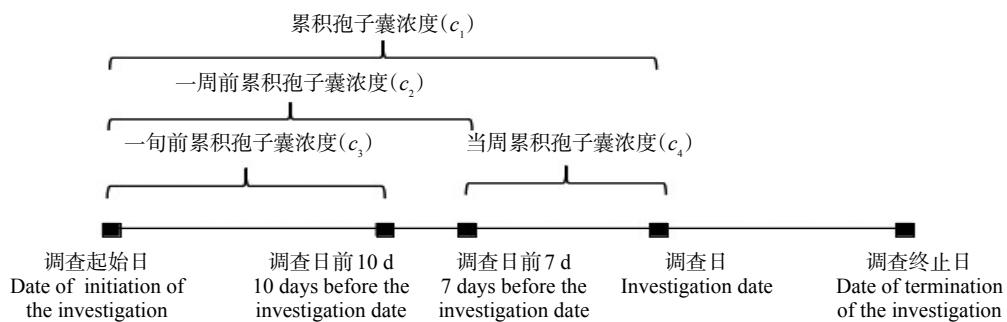


图1 不同时段的病菌孢子囊累积量示意图

Fig. 1 Schematic diagram of the accumulated sporangia concentrations in different time interval

1.3.3 数据分析 应用MS Office 2003的Excel软件进行数据处理。应用SPSS 19.0中的Bivariate correlate方法进行相关性分析,采用Spearman相关系数,得到各两组变量相关的分析结果。葡萄霜霉病的病情指数(Y)和孢子囊累积量(c_1 、 c_2 、 c_3 和 c_4)为因变量和自变量,通过SPSS 19.0软件进行模拟。选取对数函数(Logarithmic)、逆函数(Inverse)、复合函数(Compound)、幂函数(Power)、S型函数(S)、生长函数(Growth)、指数函数(Exponential)和逻辑斯蒂函数(Logistic)等8种常用曲线模型对2016—2019年实测数据进行拟合,以各模型的决定系数(R^2)、F值(F)、显著性概率(p)和估算标准差(Std E)作为模型取舍的标准,筛选出最佳模型。

2 结果与分析

2.1 葡萄霜霉病田间病情发展动态

图2为2016—2019年沈阳地区葡萄霜霉病的病情增长情况。葡萄霜霉病季节流行曲线通常表现为S形曲线,始发期为7月上旬至下旬,此时期葡萄叶片上可供侵染的位点充裕,发生重叠侵染的可能性很小,病害的自我抑制作用不明显,病害呈指数增长;盛发期为7月下旬至8月下旬,此期间随着病情迅速扩展,田间葡萄健叶上可供侵染的位点逐渐减

少,重叠侵染增多,病害的自我抑制作用不断增强,病情呈现逻辑斯蒂增长;衰退期为8月下旬至9月中旬,葡萄叶片上可供侵染的位点已近饱和,病情增长趋于停止,流行曲线渐趋平稳。不同年度葡萄霜霉病始发时间和流行程度均有一定差异,这与气象因素中的降雨量存在密切关系。2016年6月下旬累积降雨量为107.1 mm,显著大于2017—2019年同期的降雨量(7.5 mm、5.6 mm和0.0 mm),因此2016年7月1日即发现小区内有病叶显症,明显早于其他3年病害始发时间7 d以上(2017年7月7日、2018年7月8日和2019年7月10日)。2016和2019年生长季降雨充沛,累积降雨量(7—9月)分别为546.3 mm和446.8 mm,霜霉病流行程度加重,生长季末最大病情指数分别可达93.52和72.56;而2017和2018年降雨次数偏少,累积降雨量(7—9月)分别为305.7 mm和278.8 mm,生长季末最大病情指数仅为64.89和57.55。

2.2 田间空气中葡萄霜霉病菌孢子囊浓度变化动态

田间空气中葡萄霜霉病菌孢子囊浓度变化曲线呈现波浪式变化,其总体上随着病情的增加而上升,但存在一定波动;进入病害衰退期,随着病情趋于平缓,空气中孢子囊浓度随之逐渐降低(图3)。2016

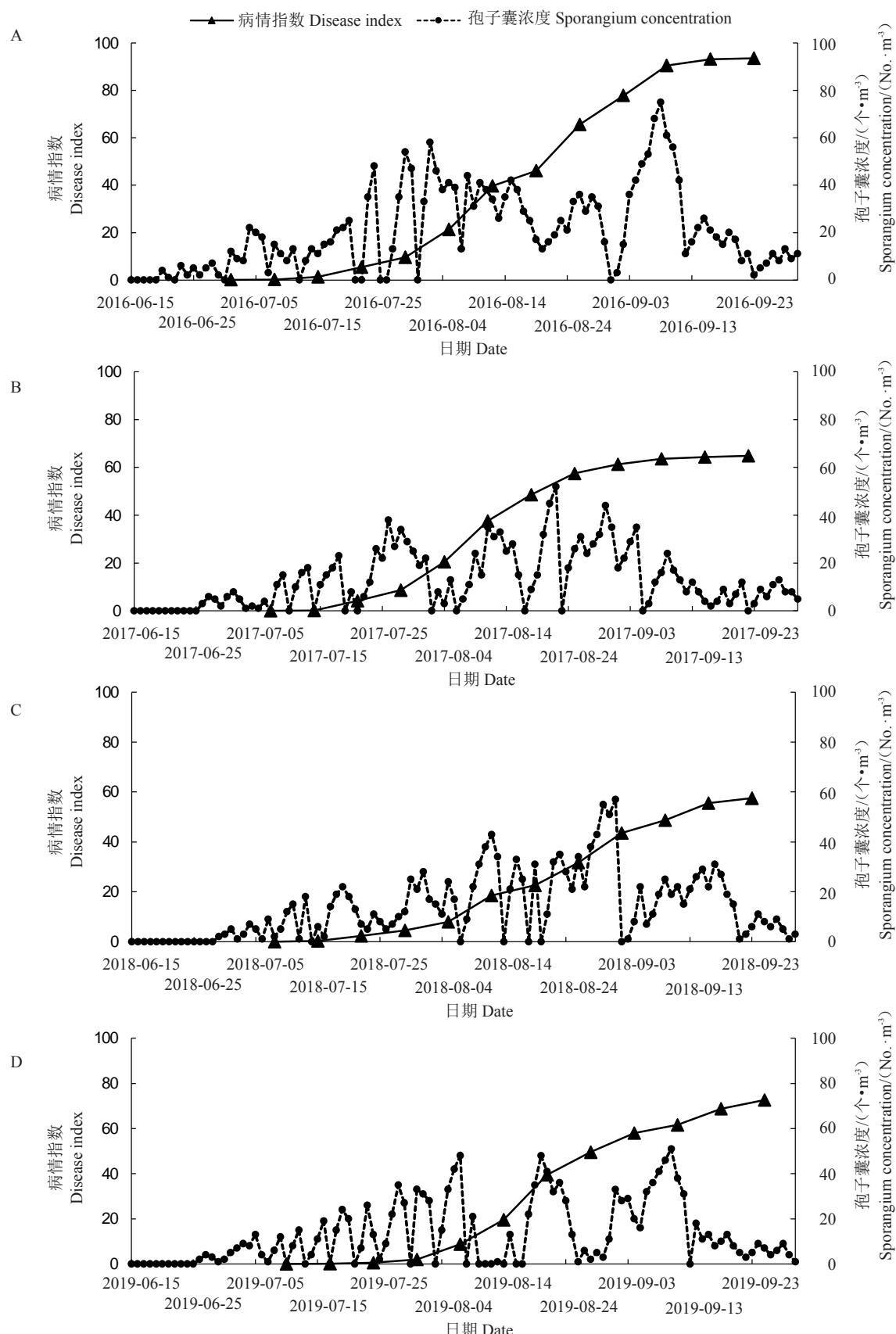


图 2 葡萄霜霉病季节流行曲线与空气中孢子囊浓度的动态变化

Fig. 2 Progress curves of grape downy mildew epidemic and dynamic of airborne sporangium concentration of *Plasmopara viticola* in the field

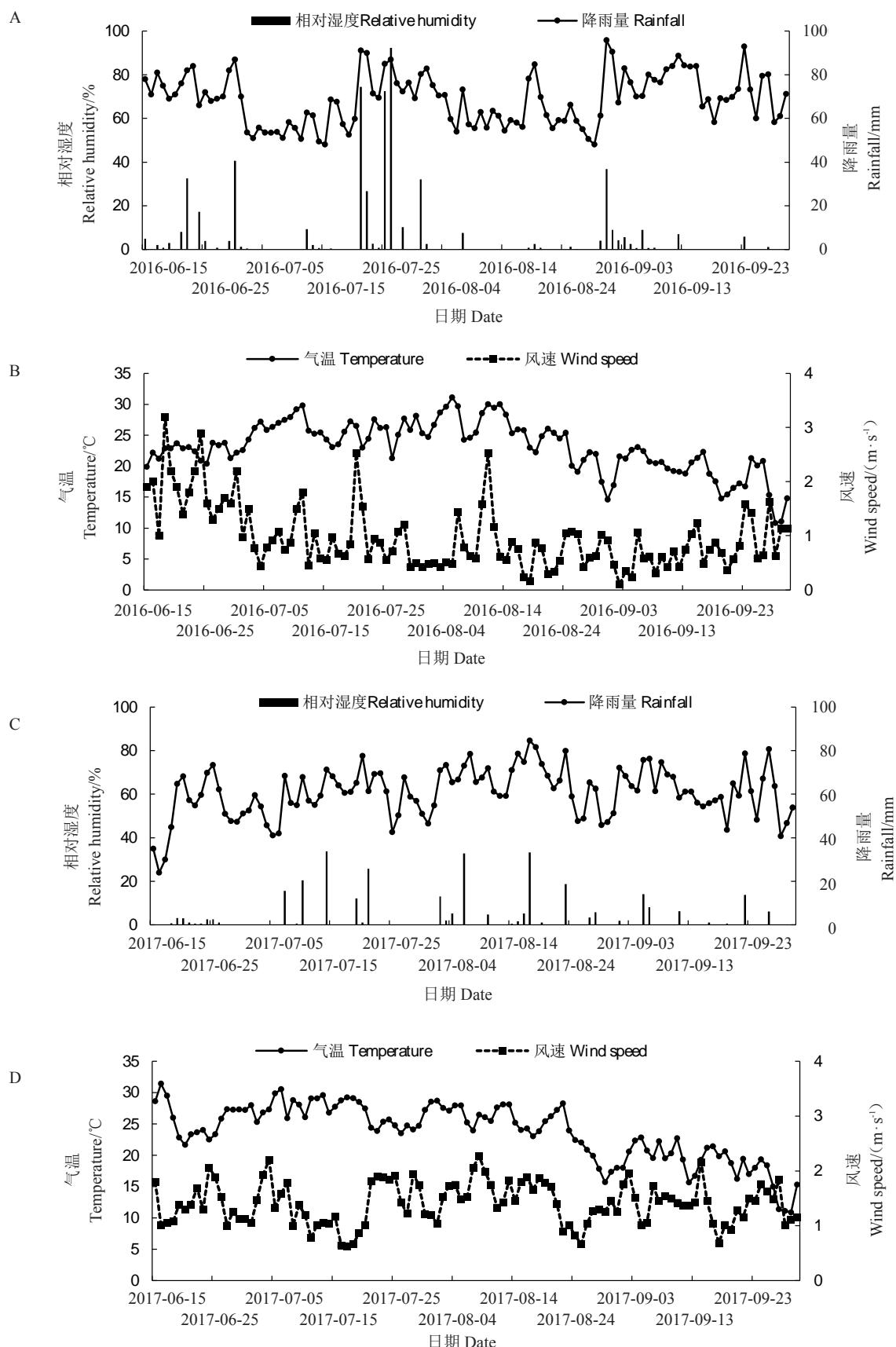


图 3 2016—2019 年葡萄生长季气象因素监测指标

Fig. 3 Dynamic of meteorological factors monitored in grape growing season during 2016 to 2019

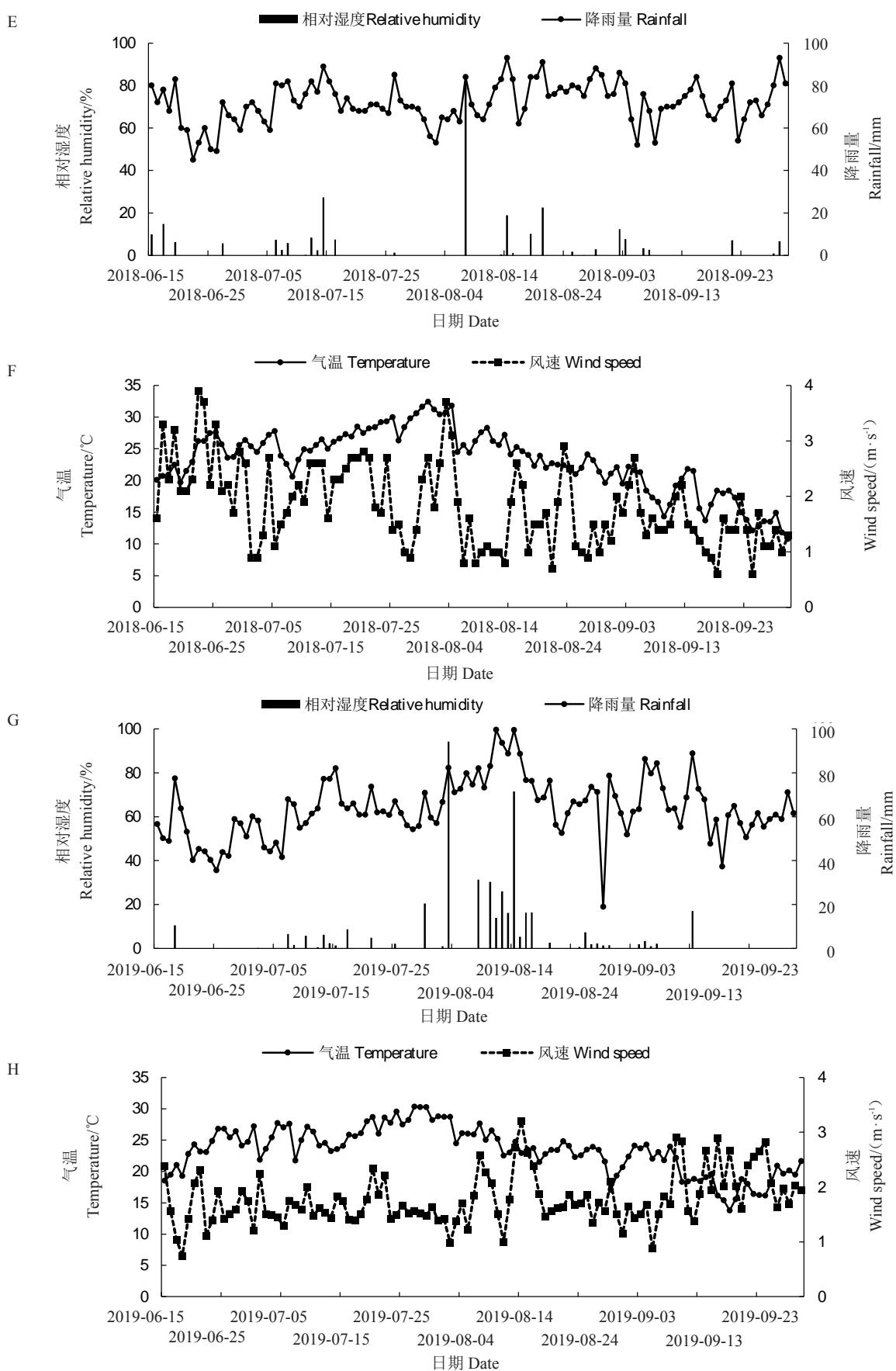


图3 (续)

Fig. 3 (Continued)

年田间首次捕孢日期为6月20日,田间空气中孢子囊浓度在7月1日前增长缓慢,随后急剧增长,于9月8日(有少量降雨0.8 mm,日均气温为20.51 °C,日均空气相对湿度为77.69%,日均风速为0.31 m·s⁻¹)达到峰值(75个·m⁻³);2017年田间首次捕孢日期为6月26日,空气中孢子囊浓度在7月11日后迅速升高,于8月22日(降雨后3 d,日均气温为28.24 °C,日均空气相对湿度为66.21%,日均风速为1.01 m·s⁻¹)达到峰值(52个·m⁻³);2018年田间首次捕孢日期为6月29日,随后空气中孢子囊浓度呈多峰性曲线上升,于9月1日(降雨后3 d,日均气温为22.10 °C,日均空气相对湿度为76.57%,日均风速为1.98 m·s⁻¹)

达到峰值(57个·m⁻³);2019年田间首次捕孢日期为6月26日,空气中孢子囊浓度在7月12日前在较低水平下波动,9月10日(降雨后3 d,日均气温为18.30 °C,日均空气相对湿度为63.67%,日均风速为2.83 m·s⁻¹)达到峰值(51个·m⁻³)。

2.3 田间空气中葡萄霜霉病菌孢子囊浓度与气象因素的相关性分析

由表1可知,2016—2019年田间空气中葡萄霜霉病菌孢子囊浓度与日累积降雨量呈显著负相关,相关系数分别为-0.233、-0.454、-0.475和-0.557,说明当日降雨对空气中孢子囊飞散有明显冲刷作用,导致空气中孢子囊浓度显著降低。除了2016年田

表1 2016—2019年葡萄霜霉病菌孢子囊浓度与气象因子的相关性分析

Table 1 Correlation coefficients between daily sporangium concentration of *Plasmopara viticola* and meteorological factors during 2016 to 2019

气象因子 Meteorological factors	孢子囊浓度 Sporangium concentration			
	2016	2017	2018	2019
日均气温 Daily average temperature	r=0.113 p=0.215	r=0.006 p=0.953	r=0.007 p=0.948	r=0.109 p=0.287
日均相对湿度 Daily average relative humidity	r=-0.079 p=0.456	r=-1.270 p=0.215	r=-0.137 p=0.188	r=-0.143 p=0.162
日累积降雨量 Daily rainfall	r=-0.233* p=0.025	r=-0.454* p<0.001	r=-0.475* p<0.001	r=-0.557* p<0.001
日均风速 Daily average wind speed	r=-0.211* p=0.044	r=-0.010 p=0.922	r=-0.117 p=0.263	r=-0.083 p=0.418
前7d平均气温 Average temperature before 7 days	r=0.164 p=0.119	r=-0.066 p=0.520	r=0.006 p=0.952	r=-0.074 p=0.473
前7d相对湿度 Average relative humidity before 7 days	r=0.268** p=0.010	r=0.351** p<0.001	r=0.224* p=0.030	r=0.250* p=0.014
前7d累积降雨量 Accumulated rainfall before 7 days	r=0.284** p=0.006	r=0.381** p<0.001	r=0.131 p=0.209	r=0.209* p=0.040
前7d平均风速 Average wind speed before 7 days	r=-0.417** p<0.001	r=0.184 p=0.072	r=-0.136 p=0.191	r=-0.182 p=0.074

注:*指在0.05水平下显著相关;**指在0.01水平下显著相关。

Note: * indicates significant correlation at 0.05 level; ** indicates significant correlations at 0.01 level.

间空气中葡萄霜霉病菌孢子囊浓度与日均风速存在显著负相关外(二者的相关系数为-0.211),综合其他年度来看,田间空气中葡萄霜霉病菌孢子囊浓度与日均气温、日均相对湿度和日均风速无显著相关性,说明当日气象因子并非是影响葡萄霜霉病菌孢子囊飞散的关键因素。

2016和2017年田间空气中葡萄霜霉病菌孢子囊浓度与前7d相对湿度均呈极显著正相关,相关系数分别为0.268和0.351;2018和2019年二者呈显著正相关,相关系数分别为0.224和0.250。2016和2017年田间空气中葡萄霜霉病菌孢子囊浓度与前7d

累积降雨量均呈极显著正相关,相关系数分别为0.284和0.381;2019年二者呈显著正相关,相关系数为0.209;而2018年二者则无显著相关性,相关系数为0.131。除了2016年田间空气中葡萄霜霉病菌孢子囊浓度与前7d平均风速之间呈极显著负相关之外(二者的相关系数为-0.417),田间空气中葡萄霜霉病菌孢子囊浓度与前7d平均气温和前7d平均风速之间均无明显的相关关系(表1)。

2.4 基于累积孢子囊浓度的田间葡萄霜霉病病情预估模型的构建及检验

分别以葡萄霜霉病的病情指数(Y)和孢子囊累

积量(c_1, c_2, c_3 和 c_4)为因变量和自变量,利用SPSS 19.0中曲线估计程度选择对数函数、逆函数、复合函数、幂函数、S函数、生长函数、指数函数和逻辑斯蒂函数等8种常用曲线模型对2016—2019年实测数据进行拟合。以2016年数据为例,其中因变量(Y)为

葡萄霜霉病的病情指数,自变量(c_1)为累积孢子囊浓度,各个模型的判定系数越接近1、F值越大、显著性概率和估算标准差越小,表明模型拟合效果越好。从表2可以看出,幂模型的各个拟合度参数为上述8种模型中最高,这说明病情指数与累积孢子

表2 基于累积孢子囊浓度的田间葡萄霜霉病病情预估模型的构建及检验

Table 2 Different models between disease index and the accumulated sporangium concentration of *Plasmopara viticola*

模型类型 Model	模型表达式 Model expression	判定系数 R^2	F值 F value	显著性概率 p	估算标准差 Std E
对数函数 Logarithmic	$Y=22.834\ln c_1-60.751$	0.693	20.340	0.001	19.851
逆函数 Inverse	$Y=-250.441/c_1+42.504$	0.249	2.983	0.118	31.062
复合函数 Compound	$Y=0.459\times(1.030)^{c_1}$	0.751	27.190	0.001	1.367
幂函数 Power	$Y=0.002c_1^{2.073}$	0.976	371.630	<0.000 1	0.422
S函数 S	$Y=\exp(3.359-32.647/c_1)$	0.723	23.472	0.001	1.443
生长函数 Growth	$Y=\exp(-0.780+0.029c_1)$	0.751	27.190	0.001	1.367
指数函数 Exponential	$Y=0.459\exp(0.029/c_1)$	0.751	27.190	0.001	1.367
逻辑斯蒂函数 Logistic	$Y=1/[0.010+3.138\exp(0.961c_1)]$	0.884	68.414	<0.000 1	1.158

囊浓度多呈幂函数关系,此模型是模拟田间葡萄霜霉病病情预估的最佳模型。

从表3可以看出,以基于一周前累积孢子囊浓度构建的病情指数预估模型的拟合度最高,其判定系数最接近1(2016年 $R^2=0.989$,2017年 $R^2=0.931$,2018年 $R^2=0.979$,2019年 $R^2=0.980$)、F值最大(2016年 $F=788.154$,2017年 $F=135.840$,2018年 $F=470.811$,2019年 $F=490.694$)、显著性概率最低(2016—2019年 $p<0.0001$)和估算标准差最小(2016年Std E=0.291,2017年Std E=0.712,2018年Std E=0.375,2019年Std E=0.405)。以基于累积孢子囊浓度构建的病情指数预估模型的拟合度次之,而以旬前累积孢子囊浓度和当周累积孢子囊浓度构建的病情指数预估模型的拟合度则均不理想。

3 讨论

本研究明确了沈阳地区葡萄霜霉病季节流行曲线通常为S形曲线,始发期为7月上旬至下旬,盛发期为7月下旬至8月下旬,衰退期为8月下旬至9月中下旬。在众多气象因素中,降雨是影响葡萄霜霉病始发时间和流行程度的关键因子,这与国内外学者的研究结果一致^[7-9, 18],表现为病害的初侵染通常在一场降雨后随之发生,而在病害流行期内的降雨会引起再侵染频繁发生。除了气象因素之外,葡萄霜霉病的发生和流行也受到寄主品种抗性、菌源

表3 基于不同时段累积孢子囊浓度的田间葡萄霜霉病病情预估模型的构建及检验

Table 3 The models between disease index and the accumulated sporangium concentration of *Plasmopara viticola* in different periods during 2016 to 2019

年份 Year	模型 Model	判定系数 R^2	F值 F value	显著性概率 p	估算标准差 Std E
2016	$Y=0.002c_1^{2.073}$	0.976	371.630	<0.000 1	0.422
	$Y=0.015c_2^{1.694}$	0.989	788.154	<0.000 1	0.291
	$Y=0.018c_3^{2.433}$	0.883	67.902	<0.000 1	0.938
	$Y=0.002c_4^{2.987}$	0.765	29.347	<0.000 1	1.328
2017	$Y=0.001c_1^{2.290}$	0.921	117.354	<0.000 1	0.762
	$Y=0.011c_2^{1.858}$	0.931	135.840	<0.000 1	0.712
	$Y=0.007c_3^{3.116}$	0.863	62.915	<0.000 1	1.007
	$Y=0.017c_4^{2.628}$	0.390	6.405	0.030 0	2.123
2018	$Y=0.002c_1^{2.075}$	0.962	250.538	<0.000 1	0.510
	$Y=0.023c_2^{1.610}$	0.979	470.811	<0.000 1	0.375
	$Y=0.058c_3^{2.125}$	0.842	53.075	<0.000 1	1.034
	$Y=0.003c_4^{3.096}$	0.615	15.984	0.003 0	1.615
2019	$Y=0.0005c_1^{2.876}$	0.975	392.376	<0.000 1	0.452
	$Y=0.001c_2^{2.300}$	0.980	490.694	<0.000 1	0.405
	$Y=0.001c_3^{3.713}$	0.717	25.358	0.001 0	1.525
	$Y=0.004c_4^{2.938}$	0.280	3.898	0.077 0	2.432

注: c_1 . 累积孢子囊浓度; c_2 . 一周前累积孢子囊浓度; c_3 . 前一周累积孢子囊浓度; c_4 . 当周累积孢子囊浓度。

Note: c_1 . Accumulated sporangium concentration before the day of disease measuring; c_2 . Accumulated sporangium concentration before the current week of disease measuring; c_3 . Accumulated sporangium concentration in the previous week of disease measuring; c_4 . Accumulated sporangium concentration in the current week of disease measuring.

基数、病菌致病性、人为干扰等诸多因素的影响^[1, 6]。

通过分析2016—2019年的田间空气中葡萄霜霉病菌孢子囊浓度和气象因素数据,证实了葡萄霜霉病菌孢子囊是葡萄园气传微生物区系中常见的组成成分^[18]。经相关性分析,表明短期(7 d)平均相对湿度和累积降雨量是影响霜霉病菌空气中飞散的主要气象因子,这2个因子与田间空气中孢子囊浓度均呈极显著正相关,即适宜的环境条件导致空气中捕孢量增加,田间病情也会随之加重,这与之前的研究结果是一致的^[7-9];同时研究发现较强降雨(日累积降雨量≥5 mm)对空气中孢子囊有较大的冲刷作用,可大大降低空气中孢子囊浓度,导致捕孢量骤减。

连续4 a的田间监测数据表明,田间空气中病菌孢子囊浓度随着葡萄霜霉病病情曲线的增加而上升,这一结果符合前人的研究结果^[7, 18],可以构建基于田间空气中病菌孢子囊浓度的葡萄霜霉病病情预估模型。经非线性回归分析的结果表明,2016—2019年田间病情与不同时段累积孢子囊浓度均呈幂函数关系,其中田间病情与累积孢子囊浓度和一周前累积孢子囊浓度的拟合效果最佳,因此累积孢子囊浓度和一周前累积孢子囊浓度可作为田间病情预估的最佳参数。国外已有关于田间空气中孢子囊浓度的病叶严重度预测模型报道^[18],而我国的这类模型刚刚处于起步阶段,笔者在本研究中仅探讨了单一葡萄品种在单一试验地点、连续多年的葡萄霜霉病流行与空气中孢子囊浓度之间的关系,建立了基于田间空气中孢子囊累积浓度的病情预估模型,还应进一步探索其他因素如葡萄品种、作物生育期、品种抗病性、病菌致病性、施药水平等对葡萄霜霉病流行的作用,完善葡萄霜霉病流行的精准预测,为科学防治提供理论依据。

4 结 论

根据2016—2019年田间小区试验分析,沈阳地区葡萄霜霉病季节流行曲线通常表现为S形曲线,始发期为7月上旬至下旬,盛发期为7月下旬至8月下旬,衰退期为8月下旬至9月中下旬。降雨量和相对湿度可显著影响葡萄霜霉病流行和空气中孢子囊飞散程度。利用累积孢子囊浓度可预测葡萄霜霉病田间病情发生程度,二者呈幂函数关系,其中病情指数与累积孢子囊浓度和一周前累积孢子囊浓度的拟

合效果最佳。

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