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Refining Degree-Day Models for Sparganothis Fruitworm in Cranberry by Biofix and Variety

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Abstract: Timing insecticide applications with insect emergence is critical for the management of cranberry pests like Sparganothis fruitworm (*Sparganothis sulfureana*, Lepidoptera: Tortricidae). The annual peak flight of *S. sulfureana* has previously been predicted using a degree-day model with a biofix date of 1 March; however, this biofix is not suitable for regions where winter and spring temperatures are warmer and flooding of cranberry beds is relied upon, which inhibits *S. sulfureana* development. In this study, we present two new degree-day models for predicting *S. sulfureana* peak flight based on six years of trapping data from New Jersey (USA): one with a biofix of 15 April, a date when drainage of cranberry beds occurs on average, and another using individual bed drainage dates. These models project peak flights at 525.5 and 521.0 degree-days using 15 April and water draw date as biofixes, respectively. These models can be used interchangeably, with both biofixes being suitable for regional grower guidance. Furthermore, differences in *S. sulfureana* peak flight were observed across four cranberry varieties; however, the effect of variety was influenced by year (significant variety-by-year interaction). This year-to-year variation in peak flight was strongly associated with spring (April–May) temperatures. Using these models, we project that with climate change, the peak flight of *S. sulfureana* in New Jersey cranberry beds may occur up to a week earlier by 2050. The use of a region-specific biofix and variety-specific models will help to better refine degree-day models for *S. sulfureana*, allowing for improved timing of management strategies against this pest.

Keywords: *Sparganothis sulfureana*; Tortricidae; *Vaccinium macrocarpon*; peak flight; trapping; phenology; model simulation; climate

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1. Introduction

Accurate prediction of a pest's phenology is a crucial component of decision-making in any integrated pest management (IPM) program [1–3]. Annual developmental predictions can be assisted by developing degree-day models that use ambient temperatures and are typically initiated after a specific calendar date or a biological event, such as the emergence of adult pests, referred to as a 'biofix' [4–6]. Thus, a biofix can be a key parameter in improving the timing of pest control interventions. Although degree-day models have been developed for hundreds of insect pests [7], their accuracy can depend on factors such as the use of an appropriate biofix, the type of crop or variety, or the regional environmental conditions.

The American cranberry, *Vaccinium macrocarpon* Aiton, is a small fruit crop primarily cultivated in its native North American range, with Wisconsin, Massachusetts, and New Jersey being the leading producing states in the USA [8,9]. A significant pest affecting this crop in these regions is the Sparganothis fruitworm, *Sparganothis sulfureana* Clemens

(Lepidoptera: Tortricidae) [8,10–13]. Also native to North America, *S. sulfureana* overwinter as early-instar larvae, which become active in the spring, after which the first-generation adults emerge during summer, coinciding with the cranberry bloom [10,12–15]. Eggs are laid by the end of bloom and hatch around the time when fruit sets. The larvae from this second generation are the most damaging to the crop, since they feed on the developing fruit [10,15]. To prevent crop injury, populations of *S. sulfureana* are monitored before the bloom using sweep net sampling to assess larval infestation [10,12,15]. During the bloom, traps baited with the sex pheromone are deployed to assess adult activity [10,12,15].

Timing insecticide applications to manage *S. sulfureana* can be challenging, and degree-day models can be developed based on male counts from pheromone-baited traps to better time these applications [14,16]. In a previous study, Deutsch et al. [16] found that the peak flight of *S. sulfureana* in cranberry beds in Wisconsin can be modeled using a sigmoidal curve of the cumulative seasonal trap catch percentage versus cumulative degree-days, similar to the findings of Cockfield et al. [14]. The peak flight was predicted to occur at the degree-day value corresponding to 50% of the modeled catch. Using this approach, Deutsch et al. [16] found that *S. sulfureana*'s peak flight in Wisconsin cranberry beds occurs around 491.2 $\pm$ 11.1 degree-days, using a biofix of 1 March and a degree-day calculation ranging between 10 °C and 30 °C. The peak flight estimate could serve as a valuable indicator for timing insecticide applications to target second-generation larvae before they burrow into the fruit and reduce the yield, which typically takes place 10–14 days post-peak flight [15].

Still, there are limitations to the applicability of the degree-day model developed by Deutsch et al. [16] in other cranberry-producing regions. The Rutgers IPM Program in New Jersey has received grower feedback that the spray advisories guided by the Deutsch et al. [16] model do not seem to be effective, and many have subsequently ignored the model-based advisories. Deutsch et al. [16] utilized a calendar-based biofix of 1 March because temperatures in January and February are generally cold enough to preclude *S. sulfureana* development in many cranberry-growing regions, including Wisconsin. Thus, the model assumes that degree-days are not typically accumulated before this time and begin to do so afterward, particularly if there is a warm spring [13,14]. However, this assumption is different for New Jersey due to different winter flooding practices. The practice of flooding and draining the beds varies geographically. For example, in Wisconsin and during particularly cold conditions in Massachusetts, a layer of ice can form on top of the flooded bed during winter, and growers will periodically drain the water under that ice if oxygen levels are low [17]. In New Jersey and during warmer Massachusetts conditions, the beds typically remain flooded throughout the winter and early spring, not being able to develop a substantial ice layer. Additionally, in New Jersey, cranberry beds are typically drained closer to 15 April, though there is substantial variation around this average date.

Sparganothis sulfureana overwinter in the early larval stage in flooded beds and come out of hibernation with new growth in the spring [12,18]. Cranberry buds break dormancy in the spring after the winter flood has been removed in response to warming temperatures [19]. The timing of the winter flood removal influences spring growth such that the earlier the flood is removed, the earlier the plant can accumulate heating units and break dormancy [19]. In this way, the presence of the winter flood in New Jersey lasting until early-to-mid-April inhibits the development of the cranberry plant by insulating the plant from warmer spring temperatures, and the *S. sulfureana* larvae follow suit. This effect has been observed anecdotally by researchers and growers, where early-instar *S. sulfureana* larvae within New Jersey beds are only found after complete water removal, until later into the spring season [18,20]. Therefore, even if there is a warmer period before water draw, it appears that the larvae do not accrue developmental warming. Given this cultural flooding practice in New Jersey, and how the winter flood likely inhibits development, it would be appropriate to re-evaluate the use of the 1 March biofix in New Jersey at a later date.

This triggering mechanism, i.e., the drainage of the beds, also raises the question of whether using a universal biofix date, such as 1 March or 15 April, is more appropriate than using the date of individual bed water draw (drainage), which could vary by up to a month among different beds. Another limitation is that the existing degree-day model does not account for cranberry variety. The history of cultivation and phenology are different among cranberry varieties, which could influence the development of *S. sulfureana*. Beds of different cranberry varieties may experience different peak flight timings of *S. sulfureana* and, therefore, may require different timelines for insecticide application. The varieties monitored in this study were Ben Lear (BL), Crimson Queen (CQ), Demoranville (DM), Early Black (EB), Haines (HN), Mullica Queen (MQ), and Stevens (ST). ST and MQ are currently the most planted varieties in North America [21]. EB and BL originated from native selections planted in the early and mid-20th century in New Jersey, Wisconsin, and Massachusetts (USA). ST is an early hybrid variety from initial breeding efforts to manage blunt-nosed leafhoppers, *Limotettix vaccinii* Van Duzee, the vector of the phytoplasma that causes false blossom disease in cranberries [22]. CQ, DM, HN, and MQ are modern hybrids released since 2006 and are primarily selected for enhanced fruit quality and productivity [22,23].

In this study, we sought to refine the peak flight degree-day model for *S. sulfureana* based on the biofix date and cranberry variety for improved use in New Jersey. We hypothesized that the accuracy of degree-day models in estimating *S. sulfureana* peak flight is influenced by the biofix date and cranberry variety. Specifically, we used multi-year (2016–2021) trapping data from multiple New Jersey cranberry beds to investigate whether the pest's flight activity during the growing season is affected by three different biofix dates—1 March, 15 April, or the date of bed water draw—and seven different cranberry varieties. Additionally, we developed projected models using predicted future climate data. These findings are important for improving the accuracy of degree-day models for *S. sulfureana* and optimizing the timing of insecticide applications.

2. Materials and Methods

2.1. Study Site and Experimental Design

Data on *S. sulfureana* trap captures were collected from 32 cranberry beds located in Chatsworth, New Jersey, within the Atlantic Coastal Pine Barrens ecoregion, over a six-year period from 2016 to 2021. In each bed, one Pherocon trap (Trécé Inc., Adair, OK, USA) baited with the *S. sulfureana* sex pheromone (Trécé Inc.) was used. The traps were mounted on poles directly above the cranberry canopy, with approximately one trap per 10 hectares. The number of *S. sulfureana* males captured in each trap was recorded weekly, and the traps were cleared of *S. sulfureana* and rebaited as needed to prepare for the following week's captures. Each cranberry bed therefore had continuous weekly sampling across the trapping season, with one weekly maintained trap per bed. Note that in 2016, the traps were checked more frequently, as the surveying effort started to ensure efficacy, but the total number of survey weeks was five. The trapping season started from 1 June and ran as late as 31 July, with the length determined by when peak flight was able to be identified and *S. sulfureana* flight activity in the bed decreased. This results in an annual variation in the number of weeks surveyed ranging from four to ten (Table 1).

The sampling period covers early bloom, when adults from the first generation start to emerge, to fruit maturation, which corresponds to the end of the adults' flight. The pheromone lures were changed biweekly. The number of beds sampled (and traps deployed) per variety varied annually, with the total number of traps ranging from 33 to 47 throughout the study period (Table 1). This variation is to be expected when sampling on working lands, where the grower may alter varietal acreage or introduce new varieties over the survey period (such as the Haines [HN] variety being introduced into the program in 2020) as needed for operations or marketability.

Additionally, for each bed, the cranberry variety and annual water draw date were documented. These factors may influence the timing of peak flight activity within each bed, as the water draw date serves as the starting point for *S. sulfureana* larval development in that location, with the trapping season occurring after adult emergence and flight starting in June. The water draw dates were recorded for each bed and converted to Julian calendar dates for analysis. These dates vary annually due to weather conditions and grower scheduling but typically range from Julian day 81 (21 March) to Julian day 120 (30 April), with an average of Julian day 105 (15 April) across all years. For more details on specific water draw timings, refer to the unprocessed dataset available at https://osf.io/rhz2w/, accessed on 11 December 2024.

Table 1. Number of beds monitored by year and cranberry variety with the duration of the annual trapping season that was able to capture peak flight.

Year	BL	CQ	DM	EB	HN	MQ	ST	Total
2016 (5)	12	4	1	9	0	0	7	33
2017 (6)	12	5	2	7	0	1	9	36
2018 (5)	12	5	2	8	0	2	10	39
2019 (4)	12	5	2	8	0	4	9	40
2020 (5)	12	6	2	8	1	5	9	43
2021 (8)	12	7	2	9	2	5	10	47

BL = Ben Lear, CQ = Crimson Queen, DM = Demoranville, EB = Early Black, HN = Haines, MQ = Mullica Queen, ST = Stevens. The number in parentheses next to the year indicates the number of weeks sampled in that year. There was one continuous trap placed per bed for the survey season.

Daily weather data were obtained from a weather station in Chatsworth, New Jersey, operated by the Office of the New Jersey State Climatologist (https://climate.rutgers.edu/stateclim/, accessed on 10 December 2024). We utilized the daily average temperature records available from this station, which were complete and without gaps between 2016 and 2021.

2.2. Initial Degree-Day Model

We first analyzed the performance of the Deutsch et al. [16] model for predicting peak flight against *S. sulfureana* captures in New Jersey cranberry beds. Using a biofix date of 1 March, we recorded degree-days until peak flight. The peak flight data were collected by variety and for all the surveyed beds combined. The peak flight was determined using the methodology of Deutsch et al. [16] by fitting a sigmoidal model to the running capture percentage. Initially, the average number of captures per sampling day at each site was converted into a running percentage for the trapping season, ranging from 0% at the start to 100% at the end of the season. At each capture date, cumulative degree-days from 1 March were also recorded. Using percent capture as the dependent variable and degree-days as the independent variable, a sigmoidal model was fit to these data by variety and for all the beds combined using the fit function in MATLAB (ver. 9.14.0.2337262; Mathworks, Natick, MA, USA).

The sigmoidal model is given by the following:

$$f(x) = \frac{a}{1 + e^{\frac{-(x - x_0)}{b}}} \quad (1)$$

where x is the degree-days in Celsius ($DD_{\circ C}$), a and b are computationally derived fit parameters, and x_0 is the degree-days associated with peak flight (i.e., the inflection point of the sigmoidal curve, representing 50% capture for the season).

2.3. Refining the Degree-Day Model by Biofix

In refining this degree-day model, we sought to identify if there is a more appropriate biofix for New Jersey. Specifically, we sought to establish a New Jersey-specific biofix based on the winter flood water removal (here forward: water draw), as it presents the potential to affect *S. sulfureana* development out of larval winter dormancy due to the water inhibiting spring cranberry growth [12,18–20]. As water draw in New Jersey is typically around mid-April, using an earlier biofix could lead to overestimation of development during a warm March followed by a cooler April, leading to errors in projecting peak flight. We explored two potential biofixes: one based on physical agricultural processes (i.e., water draw date) and another based on a calendar date. During winter, cranberry beds are flooded to protect the plants from freezing temperatures [17]. In the spring, these beds are drained to allow for cranberry development. Draining the beds also initiates overwintered *S. sulfureana* larval development in the spring [12,18,20], which are found in recently drained beds in their overwintering instar form after draining. Thus, we selected the timing of water removal in the spring to evaluate as a site-specific biofix for projecting peak flight.

We also tested a calendar day biofix of 15 April (annual day 105) each year to serve as a more convenient biofix for region-wide application, providing that bed-specific guidance across all of New Jersey's cranberry farms might be impractical. 15 April was used because it closely coincides with the average water draw date across all the surveyed beds. For both biofixes, a sigmoidal model (Equation (1)) was fit to the data to model the peak flight in degree-days.

2.4. Refining the Degree-Day Model by Variety

Additionally, we investigated whether peak flight is influenced by cranberry variety. Three different biofixes—1 March, 15 April, and water draw dates—were employed to analyze varietal differences in modeled peak flight. Specifically, we developed distinct degree-day models for peak flight across four cranberry varieties: ST, CQ, EB, and BL. Of the total surveyed varieties, the acreage of newer varieties (DM, HN, and MQ) is relatively low in New Jersey; thus, we did not include these varieties from the varietal analysis to improve statistical robustness because the average annual number of beds sampled was less than five. For each of the remaining varieties (ST, CQ, EB, and BL) and each biofix, we applied the sigmoidal function (Equation (1)) to fit the data, resulting in a total of 15 different models (12 models by variety and 3 models that included captures from all the varieties).

2.5. Data Analysis

The trapping data were used to assess if the number of degree-days for peak flights varied by variety, biofix, and year. This analysis aimed to determine if the refined biofixes based on water draw and 15 April differ from the original 1 March biofix. It also tested whether the four cranberry varieties with an average of five or more monitored beds per year benefit from a specific model fit compared to a general model for all the varieties.

Statistical analyses were conducted using RStudio with R version 3.02.3 [24], utilizing packages including hnp, emmeans, multcomp, and dplyr. Prior to analysis, the data on the number of degree-days for peak flight were verified for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. A generalized linear model (GLM) with a gamma distribution and log link function was employed to analyze the data. The model included the main factors, namely, biofix type, variety, and year, as well as their respective interactions. Post hoc testing using Fisher's least significant difference (LSD) test was performed for each factor showing a significant effect. In addition, Pearson correlations (r) were used to correlate *S. sulfureana* peak flight degree-days with various explanatory factors, such as varietal bloom time and spring temperatures. An analysis of variance (ANOVA) was used to test whether the *S. sulfureana* peak flight degree-days were influenced by the degree of domestication among the varieties.

2.6. Climate Projections

To assess how peak flight timing—and, consequently, insecticide application schedules—might shift in response to warming spring temperatures in New Jersey, we used the 15 April biofix peak flight model in combination with future daily temperature projections. Daily projections of historic and future spring and early summer temperatures near Chatsworth, New Jersey, were obtained from the National Oceanic and Atmospheric Administration (NOAA) Regional Climate Centers' Applied Climate Information System

(ACIS) [25]. We obtained the simulated historic and future temperature time series for two warming scenarios from ACIS: shared socioeconomic pathways (SSPs) 2-4.5, representing moderate warming, and SSP3-7.0, representing high warming. Under these scenarios, global temperatures are projected to increase by 2.7 °C and 3.6 °C, respectively, by 2100 compared to preindustrial conditions [26].

The model projections accessed through ACIS were derived from the localized constructed analogs version 2 (LOCA2), which downscales data from 16 Coupled Model Intercomparison Project phase 6 (CMIP6) general circulation models [27] at an approximate spatial resolution of 4 km. For each model, the annual $DD_{\circ C}$ using the 15 April biofix were calculated from the temperature time series and the peak flight, determined by the 15 April peak flight model (Section 3.2), and the associated Julian calendar date were recorded.

These results were combined into multi-model averages of spring (March–May) warming (average temperature) and annual growing degree-days for a historical period (1991–2020) and a future mid-21st century period (2035–2065). The average historical temperatures and peak flight days were then compared to the averages for the future period under both moderate and high warming using a simple change analysis. This analysis aimed to determine how the average annual peak flight of *S. sulfureana* may shift in response to warmer spring temperatures expected during the 30-year period centered on 2050, compared to historical conditions. The results can inform long-term IPM planning by highlighting potential changes in the timing of interventions and providing a timeline for implementing these adjustments.

Additionally, changes in the spring temperatures' 10th and 90th percentiles from the model outputs were assessed to provide a holistic range of potential change. Using these projections, we examined how peak flight dates based on model outputs may differ compared to present-day conditions. For these projections, the 15 April biofix (105 Julian calendar days) was selected for ease of comparison.

3. Results

3.1. *Sparganothis sulfureana* Flight Activity

The average flight pattern of first-generation *S. sulfureana* in Chatsworth, New Jersey (USA) is shown in Figure 1, which details the average capture pattern by Julian calendar day. Moths were first detected in traps on Julian calendar day 160 and were last captured on Julian calendar day 211, spanning a total of 52 days. Full, unprocessed flight data for this study can be found in the associated dataset at https://osf.io/rhz2w/, accessed on 11 December 2024.

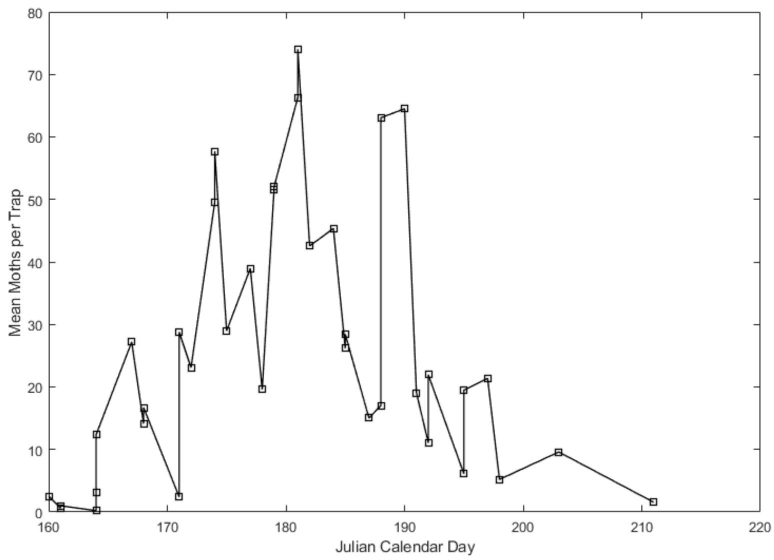

Figure 1. Mean trap captures of *Sparganothis sulfureana* across the study period by Julian calendar day.

3.2. Effect of Biofix in Degree-Day Model

For all the trapping data, the date of *S. sulfureana* peak flight ranged from 21 June to 2 July, occurring in 2019 and 2020, respectively, in New Jersey, with an average date of 24–25 June across all the years. Using these data, we created models predicting the percentage of *S. sulfureana* captures over the accumulated degree-days for each biofix—1 March, 15 April, and the water draw date (Figure 2). Table 2 presents the parameters for these predictive models based on Equation (1). These models project peak flight at 575.1, 525.5, and 521.0 $DD_{°C}$ using 1 March, 15 April, and the water draw date as biofixes, respectively (Table 2).

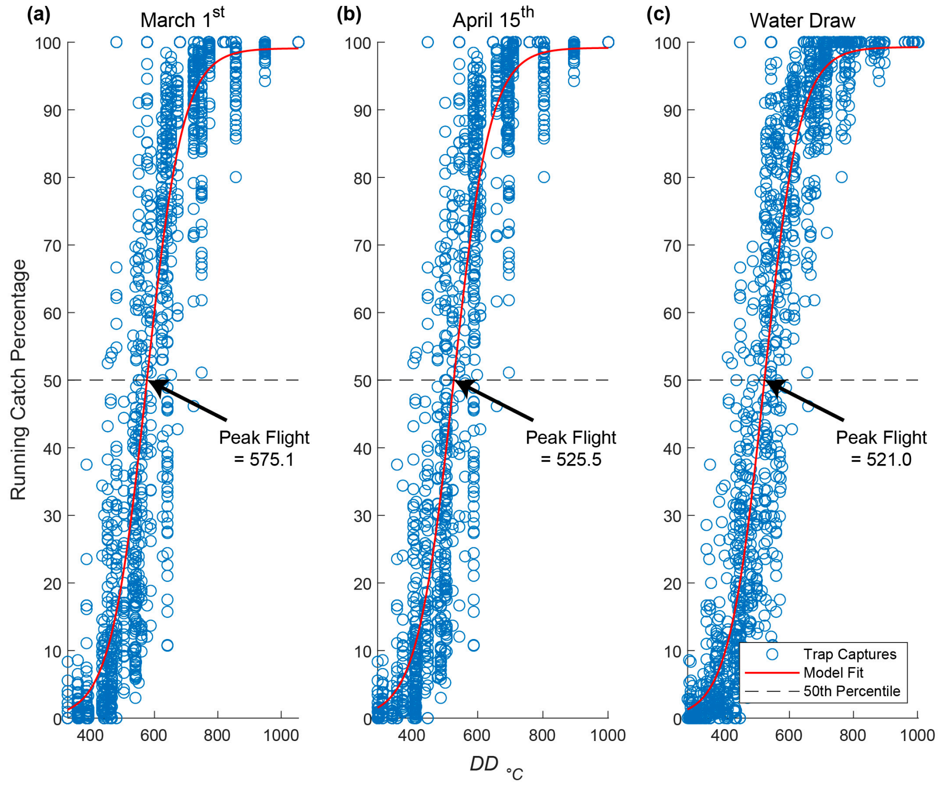

Figure 2. Sigmoidal degree-day ($DD_{°C}$) model fits of *Sparganothis sulfureana* percent seasonal capture with a biofix determined by (**a**) 1 March, (**b**) 15 April, and (**c**) the water draw date. The 50th percentile dashed line is plotted to represent the occurrence of peak flight. Arrows indicate the $DD_{°C}$ of peak flight for each model fit.

Table 2. Estimated parameters based on Equation (1) for *Sparganothis sulfureana* degree-day models by biofix.

Biofix	Parameters [1]				RMSE [2]
	a	x_0	b	r^2	
1 March	99.1 ± 0.8	575.1 ± 2.1	57.2 ± 1.8	0.87	14.55
15 April	99.2 ± 0.8	525.5 ± 2.0	56.1 ± 1.7	0.88	14.08
Water Draw	99.3 ± 0.7	521.0 ± 1.8	55.2 ± 165	0.89	13.15

[1] a and b are computationally derived fit parameters; x_0 is the degree-days associated with peak flight. Values next to each parameter represent the 95th percentile confidence interval. [2] RMSE = root mean squared error.

As expected, the degree-days required to reach peak flight were significantly affected by the biofix used, with more degree-days needed when using the 1 March biofix compared to when the 15 April or the water draw date biofixes were used (Figure 3; Table 3). There was no significant difference in the calculated degree-days between the 15 April and the water draw date biofixes (Figure 3). The difference between the 15 April and water draw biofixes was only 4.5 $DD_{\circ C}$, whereas the difference between these two biofixes and the 1 March biofix was 50–54 $DD_{\circ C}$ (Figure 3), which is expected, as the degree-day accrual occurs earlier when using 1 March. Given that the model fits are similarly good (r^2 of 0.87–0.89), each of the biofixes could be valid for use given the proper model parameters. However, given that the winter flood can inhibit spring cranberry growth and, by extension, *S. sulfureana* larvae breaking dormancy, a model accruing $DD_{\circ C}$ prior to water draw for New Jersey could begin $DD_{\circ C}$ tabulation before the larvae are physically able to develop in the flooded beds. Therefore, given that all three models provide a reasonably similar fit to the data, we decided to utilize the 15 April and the water draw date as updated biofixes to avoid this potential issue when predicting *S. sulfureana* peak flight in New Jersey.

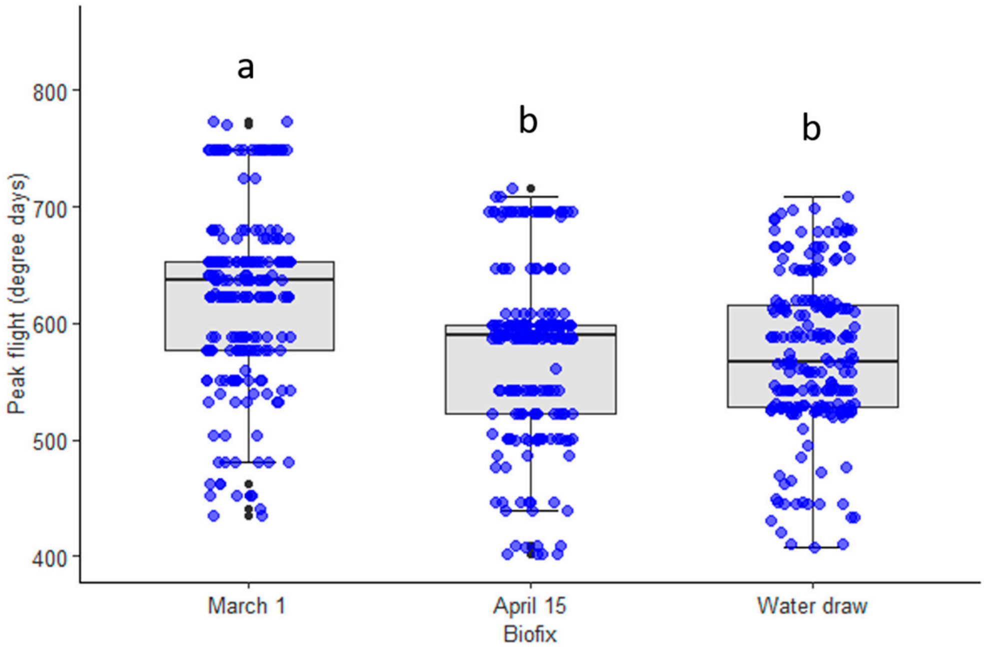

Figure 3. Box plots of *Sparganothis sulfureana* peak flight in $DD_{\circ C}$ by selected biofix. For each box, horizontal lines represent the median, boxes represent the interquartile range (25th to 75th percentiles), and whiskers represent minimal and maximal values within 1.5 times the interquartile range above and below the median. Points represent annual peak capture at each individual cranberry bed, calculated using the indicated biofix, and points outside the whisker range represent potential outliers. Different letters above the boxes indicate significant differences among the biofixes (Fisher's LSD test; $p = 0.05$), with the vertical solid line separating the two groups.

Table 3. Results of the generalized linear model (GLM) analysis for the effects of biofix, cranberry variety, year, and their interactions on the number of degree-days for *Sparganothis sulfureana* peak flight.

Independent Variables	df	χ^2	*p* Value *
Biofix	2	39.792	<0.001
Variety	3	4.682	0.0031
Year	5	30.342	<0.001
Biofix × Variety	6	0.220	0.9704
Biofix × Year	10	1.386	0.1830
Variety × Year	15	3.102	<0.001
Biofix × Variety × Year	30	0.069	1.000

* *p* values in bold indicate significance at the $p \leq 0.05$ level.

3.3. Effect of Variety on Degree-Day Model

Figure 4 shows the models predicting the percentage of *S. sulfureana* captures over the accumulated degree-days using 1 March (Figure 4a), 15 March (Figure 4b), and the water draw date (Figure 4c) as biofixes for varieties BL, CQ, EB, and ST. Table 4 presents the parameters for these predictive models based on Equation (1), using 15 April as the biofix.

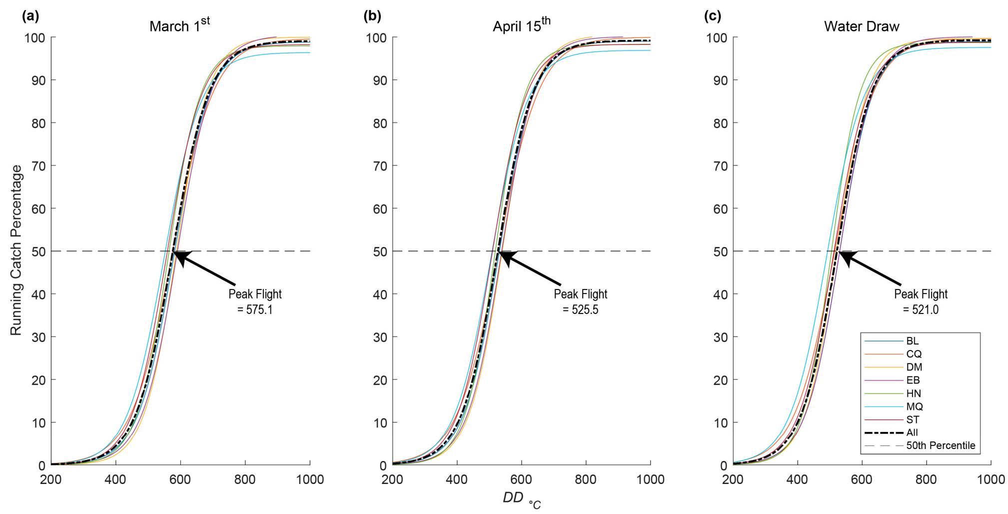

Figure 4. Sigmoidal degree-day ($DD_{\circ C}$) model fits of *Sparganothis sulfureana* percent seasonal capture for each cranberry variety with a biofix determined by (**a**) 1 March, (**b**) 15 April, and (**c**) water draw date. BL = Ben Lear, CQ = Crimson Queen, EB = Early Black, ST = Stevens. The 50th percentile dashed line is plotted to represent the occurrence of peak flight. Arrows indicate the $DD_{\circ C}$ of peak flight for model fit incorporating all varieties.

Table 4. Estimated parameters based on Equation (1) for *Sparganothis sulfureana* degree-day models by cranberry variety using 15 April (annual day 105) as the biofix.

Variety [1]	**Parameters** [2]				**RMSE** [3]
	a	x_0	b	r^2	
BL	99.0 ± 1.5	530.1 ± 3.7	55.3 ± 3.1	0.87	14.36
CQ	100.0 ± 2.5	528.0 ± 6.7	64.4 ± 5.5	0.86	14.87
EB	100.1 ± 1.7	538.3 ± 3.9	52.9 ± 3.2	0.89	13.33
ST	98.3 ± 4.5	507.8 ± 3.7	53.8 ± 3.2	0.89	13.13

[1] BL = Ben Lear, CQ = Crimson Queen, EB = Early Black, ST = Stevens. [2] a and b are computationally derived fit parameters; x_0 is the degree-days associated with peak flight. Values next to each parameter represent the 95th percentile confidence interval. [3] RMSE = root mean squared error.

We found a significant effect of variety on the degree-days required by *S. sulfureana* to reach peak flight (Figure 5; Table 3). There was no interaction between variety and biofix (Table 3). Regardless of biofix, the earliest varieties to experience peak flight were CQ and ST, while the latest were BL and EB, with a difference of about 40 $DD_{\circ C}$ between ST and EB (Table 4). The peak flight was not correlated with the time of bloom ($r = -0.434$; $p = 0.331$).

There was an interaction effect between the variety and year on peak flight (Table 3), indicating that the effect of variety varied by year. This could be due partially to the variation in spring weather conditions. For instance, there was a significant correlation ($r = 0.96$, $p = 0.002$) between degree-day accumulations from 1 April to 31 May and the spring temperature (Figure 6), with the greatest degree-day accumulated in 2018 and 2019, while they were lowest in 2020, which was the year with the coldest spring temperatures.

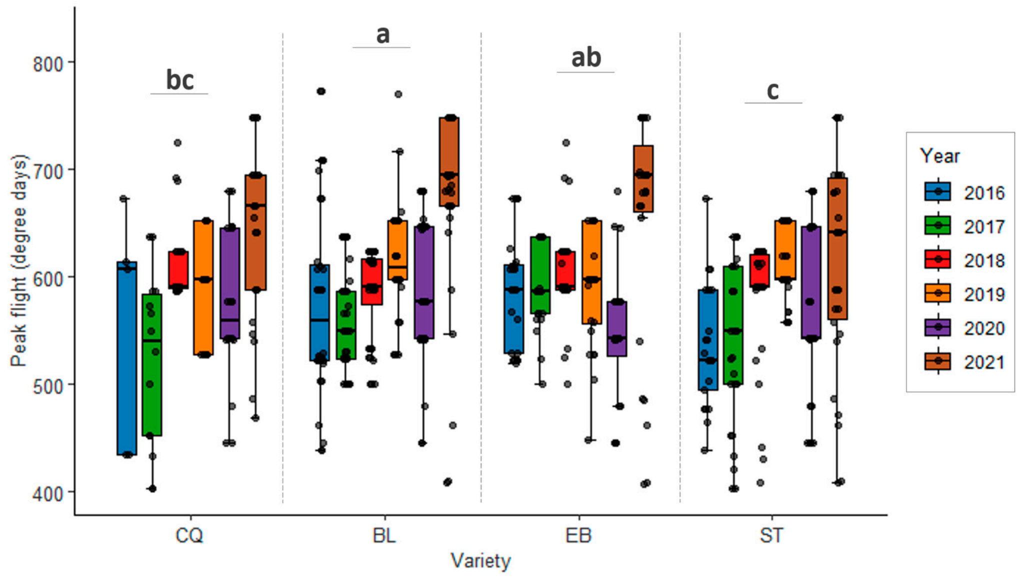

Figure 5. Box plots of *Sparganothis sulfureana* peak flight in $DD_{°C}$ using the 15 April biofix by cranberry variety across the years. For each box, horizontal lines represent the median, boxes represent the interquartile range (25th to 75th percentiles), and whiskers represent minimal and maximal values within 1.5 times the interquartile range above and below the median. Points represent annual peak capture at each individual cranberry bed, and points outside the whisker range represent potential outliers. CQ = Crimson Queen, BL = Ben Lear, EB = Early Black, ST = Stevens. Different letters above the boxes indicate significant differences among the varieties (Fisher's LSD test; p = 0.05).

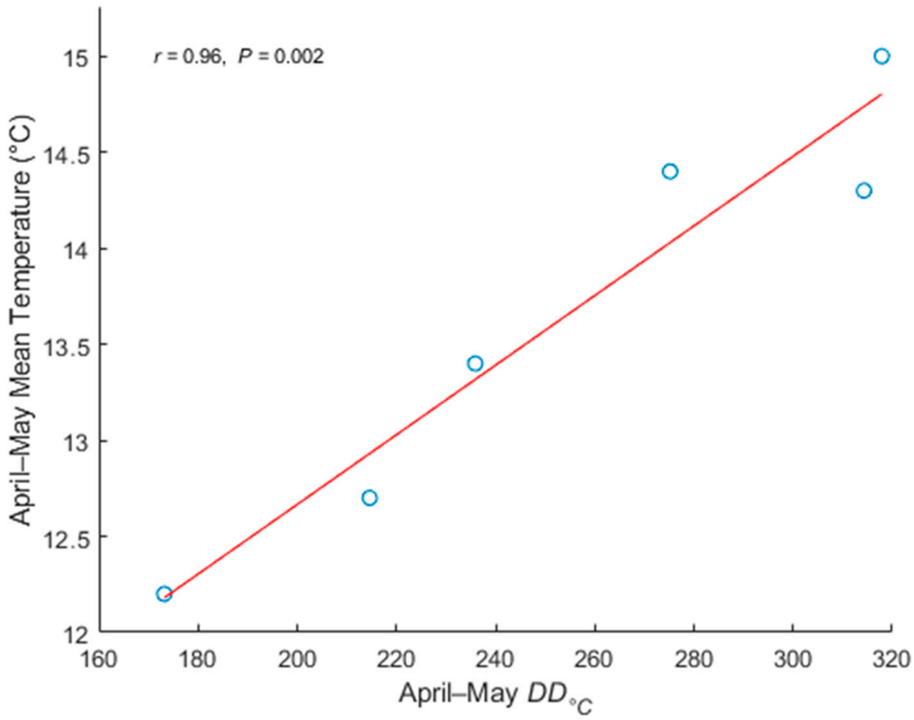

Figure 6. Correlation between the average temperature from April to May and the accumulated $DD_{°C}$ from 2016 to 2021.

3.4. Climate Projections

Under moderate climate warming (SSP2-4.5) by 2050, average spring (March–May) temperatures in New Jersey are projected to increase by 2.8 °C (Table 5). Using 15 April as a biofix, the model predicts that 525.5 $DD_{°C}$ (model for all varieties) would then occur on average by day 170.1 compared to the average annual occurrence day of 176.7 today (1991–2020). Under a high degree of climate warming (SSP3-7.0), average spring temperatures would increase by 3.0 °C, and 525.5 $DD_{\circ C}$ from day 105 would be projected to occur on average on day 169.3.

Table 5. Projected changes in spring temperatures (March–May) and when 525.5 degree-days ($DD_{\circ C}$) will occur between 2035 and 2065 (centered on 2050) compared to historical (present) spring temperatures (1991–2020) using a biofix of 15 April.

Scenario	March–May Average Temperature Change	Change in Average Annual 525.5 $DD_{\circ C}$ Date with a Biofix of Julian Calendar Day 105 (1991–2020 to 2035–2065)
SSP2-4.5	+2.8 °C (1.9–3.4)	−6.6
SSP3-3.0	+3.0 °C (2.6–3.9)	−7.4

4. Discussion

Although degree-day models are widely available to predict events and inform time-management activities (e.g., https://newa.cornell.edu/crop-and-pest-management and https://uspest.org/cgi-bin/sdb/viewdb.cgi, last access 10 December 2024), they may not consider factors such as selecting a regionally appropriate biofix reflective of local growing practices or the influence of crop variety, which may affect their accuracy. Our study demonstrates that the three biofix dates fit the *S. sulfureana* trap capture data reasonably well. However, given the potential for $DD_{\circ C}$ tabulation before water draw and the start of *S. sulfureana* spring development using the 1 March biofix, we determined that a biofix of 15 April or an event-based biofix of the water draw date can be more appropriate for regions like New Jersey given a similarly good model fit to the capture data. We also show that variety influenced the degree-days accumulated by *S. sulfureana*. Although the effect of variety did not interact with the biofix, it did interact with year. Thus, factors such as the biofix date and variety need to be considered when developing a degree-day model for *S. sulfureana*.

4.1. Influence and Interaction of Independent Variables

The three independent variables assessed for their impact on peak flight and model fit were biofix selection (calendar date vs. water draw date), cranberry variety (which influences phenology), and year (seasonal weather). Each of these variables independently and significantly influenced the peak flight of *S. sulfureana* (Table 3). However, the interaction effects of these variables on peak flight were not significant ($p > 0.05$), except for the interaction between cranberry variety and study year.

The analysis found that biofix selection was a significant factor independent of variety and year, underscoring its importance in the model for projecting peak flight. This emphasizes the need to ensure that biofix selection is appropriately represented in the model. When further subdividing biofix effects, the use of the water draw date or the 15 April proxy was significantly different from the 1 March biofix used by Deutsch et al. [16] (Figure 3). However, the 15 April and water draw biofixes did not significantly differ in their impact on peak flight $DD_{\circ C}$. This minor difference is reflected in the small improvement in model fit (R^2 and RMSE) when comparing the water draw biofix to the 15 April biofix (Table 2).

Further investigation into the interaction between cranberry variety and monitoring year, as compared to peak flight $DD_{\circ C}$, revealed that many varieties exhibited similar behavior from year to year (Figure 5). This is unsurprising, as the year variable incorporates spring temperatures, which influence phenological development, while variety affects plant phenology. In the grouping analysis, BL and ST were the main varieties that demonstrated a significant difference from the other varieties, while CQ and EB presented more of a mix, with EB behaving significantly dissimilar to ST, and CQ behaving significantly dissimilar to BL (Figure 5).

4.2. Model Analysis

For the purpose of this analysis, we compared the results presented here with the conditions and peak flight model developed by Deutsch et al. [16] for Wisconsin, as it represents the only other published *S. sulfureana* peak flight model based solely on Wisconsin data. This comparison underscores how differences in geographic regions, including local weather and cultivation systems, necessitate a reformulated peak flight model for use in New Jersey.

The 1 March biofix and its accompanying degree-day model developed for Wisconsin by Deutsch et al. [16] does not seem to apply to other cranberry-growing regions, like New Jersey, suggesting that regional effects for peak *S. sulfureana* flight need to be considered. Using 1 March as the biofix, the peak flight in New Jersey occurs at around 575.1 $DD_{\circ C}$ as opposed to 491.2 $DD_{\circ C}$ in Wisconsin, as found by Deutsch et al. [16], which would result in about a 6-day offset when considering the 15-year average spring temperatures in Chatsworth, New Jersey. This offset could result in growers not spraying during the optimal window of approximately two weeks after peak flight [18].

In addition to reconsidering the $DD_{\circ C}$ between Wisconsin and New Jersy peak flights using the 1 March biofix, we have also reconsidered whether the 1 March biofix is the most appropriate to use in New Jersey, where the cultural growing practice of winter flooding, which differs from Wisconsin's, may affect both cranberry and *S. sulfureana* development in the spring. Deutsch et al. [16] used 1 March as a logical biofix, as ambient temperatures typically preclude $DD_{\circ C}$ accumulation before March. However, the timing of the water draw in New Jersey can also affect both the cranberry plant and, by extension, *S. sulfureana* breaking winter dormancy [12,18–20], with flooded cranberry beds inhibiting *S. sulfureana* development and insulating both plant and pest from heating unit accumulation, regardless of air temperature conditions prior to the water draw. To this end, using the timing of the water draw from an individual bed as a biofix can be a logical biofix for an individual bed. Using the water draw date as the biofix, the new $DD_{\circ C}$ benchmark of peak flight across all varieties is 521.0 $DD_{\circ C}$.

There is, however, a practical concern for cranberry growers with a large number of beds or for those needing regional-scale guidance because water draw does not occur on the same day across multiple beds and can vary by several weeks. In this study, the water draw dates of the cranberry beds ranged from late March to late April, making it problematic to track the degree-days for individual beds across a large operation. Additionally, coordinating spray applications for beds with differing water draw dates throughout the growing season can be challenging. Instead, we recommend using the proxy water draw date of 15 April (annual day 105 to assist in planning during leap years), with 525.5 $DD_{\circ C}$ approximating the *S. sulfureana* peak flight for New Jersey. The difference between the modeled peak flight degree-days for the two biofixes is relatively small, and the model fits to the data were similarly good, making 15 April a good proxy for the average water draw date in the New Jersey's cranberry growing region.

Variety was also found to influence the modeled peak flight degree-days for *S. sulfureana*. However, the differences in the peak flight timing among the varieties were not particularly large, offset at most on the order of three days based on the sigmoidal model fit. As described in the methods, only the BL, CQ, EB, and ST varieties were analyzed for varietal effects. Regardless of biofix, ST had the earliest peak flight among all the varieties, while EB had the latest peak flight. Practically, when modeling the peak flight date, it could be worthwhile to use the specific model for CQ and ST, and another aggregate model for BL and EB based on the difference in peak flight timings despite the groups presented in Figure 5. The factors driving the differences in peak flight among the varieties remain unclear. Domesticated plants are usually more susceptible to herbivory due to potential trade-offs between defense and growth/reproduction [28,29], which could affect larval development and, thus, the timing of adult peak flight. While larval development can be influenced by varietal domestication and the overall quality of the host plant [30], with more resistant varieties potentially reducing larval growth [31,32], studies have not demonstrated varietal resistance against *S. sulfureana* larvae in cranberries [33,34]. This suggests that larval resistance is unlikely to account for the observed differences in peak flight among the varieties. Other yet untested factors may explain the variation in peak flight among the varieties.

The year of sampling significantly affected *S. sulfureana* peak flight degree-days, with annual spring (April–May) temperatures likely influencing the observed pattern. Although other seasonal weather factors (rainfall, frosts, etc.) may also contribute to the yearly variation of peak flight degree-days, analyzing these factors was beyond the scope of this study. We also found a significant interaction between the variety and year. Similarly, this interaction could be influenced by various factors, such as spring temperatures each year and how peak flight for each variety responds to those temperatures. Again, other environmental factors, like rainfall and environmental effects, were not accounted for in our analysis. Overall, there appears to be a more consistent grouping by year, with earlier and later years tending to be more dissimilar. However, the grouping analysis does not show consistent patterns across variety by year. Potential confounders, such as pesticides, water draw dates, and seasonal conditions, could contribute to this variability by variety but with stronger consistency in year-to-year grouping.

4.3. Future Predictions

As regional spring temperatures increase, both moderate and high climate-warming scenarios project that 525.5 $DD_{\circ C}$ from day 105 (approximately 15 April) will occur about one week earlier on average by around 2050 (2035–2065). However, there is significant year-to-year and inter-varietal variability in peak flight dates. Thus, while the calculated average is about one week earlier, there could be much earlier or later occurrences depending on spring temperatures and their volatility, which are not captured by an average. This shift can inform changes in future IPM strategies, such as planning for earlier spray timings and the potential for more cranberry damage from *S. sulfureana* due to increased exposure time to the pest. An additional complication is that as temperatures rise, the water draw date for New Jersey cranberries may change, as the growing season starts earlier. Consequently, these models would need to be re-evaluated for future consistency. Ideally, using the water draw biofix and the calculated peak flight degree-days should still be applicable under a changing climate.

An additional consideration is that this study utilized air temperatures measured at a nearby weather station, which is designed to provide regional synoptic weather information rather than highly localized data specific to individual cranberry beds. While an argument can be made that local cranberry beds or canopy temperatures might be more informative and could influence varietal differences when projecting *S. sulfureana* peak flight, it would be impractical for growers to monitor temperatures at individual beds and canopies, especially for large cranberry-growing operations. Instead, the scope of this study was to define a degree-day model for peak flight that could be used for regional guidance. To that end, regional temperatures from a local weather station were selected to inform the model and to provide practical, regional-scale guidance for New Jersey cranberry growers.

Finally, while the base temperatures for the $DD_{\circ C}$ calculations are determined by *S. sulfureana* developmental biology, this study demonstrates that other regional factors must be considered when developing and applying predictive peak flight models. The biofix can be influenced by local climates and cultural practices, such as bed flooding and water removal. If the biofix shifts due to regional and cultural factors, the degree day of peak flight will also vary, requiring a regional recalibration of the model. Additionally, cranberry variety can differ by region, which may also necessitate model recalibration. As a next step, it would be valuable to validate the developed model in regions with similar cranberry-growing practices to New Jersey and establish a methodology for recalibrating the model to account for these regional effects.

5. Conclusions

This study developed a refined degree-day model for *S. sulfureana*, calibrated to New Jersey conditions, a major cranberry producer in the US. This model tested two new biofixes: a calendar-based biofix of 15 April and an event-based biofix according to the date when water is drawn off at a specific bed. We found that both biofixes were very similar and could be used interchangeably: 15 April for practical or large-scale guidance and the water draw date for bed-level management. We further investigated the influence of cranberry variety on the peak flight timing of *S. sulfureana*. Our findings suggest that cranberry variety can affect the degree-day timing of peak flight; however, it is important to note that this timing can vary due to seasonal weather conditions. Weather and other environmental factors can cause significant differences in the interaction of peak flight timing by variety from year to year. As water draw and phenological development are mediated by spring temperatures and weather, warming temperatures associated with climate change will likely cause peak flight to occur earlier in the growing season. We investigated two warming scenarios, representing moderate and high degrees of warming, and found that the modeled peak flight degree-day would occur about 6–7 days earlier for both scenarios by approximately 2050. These findings provide insights into the use of region-specific biofixes and variety-specific models for *S. sulfureana*, allowing for improved timing of management strategies against this pest.

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Data Availability Statement: The minimal dataset underlying this work is publicly available at: https://osf.io/rhz2w/ (https://doi.org/10.17605/OSF.IO/RHZ2W), accessed on 11 December 2024. This dataset accounts for 61 cranberry beds, including *S. sulfureana* annual trap monitoring data, bed variety, and the annual date of winter flood water draw between 2016 and 2021. Meteorological data can be obtained by request from the New Jersey Weather Network (https://www.njweather.org/, accessed on 11 December 2024) operated by the Office of the New Jersey State Climatologist.

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