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Short communication

Development and validation of a new climate-driven phenological prediction model for codling moth, *Cydia pomonella*

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Abstract

Codling moth, Cydia pomonella (L.) (Lepidoptera: Tortricidae), is a key pest of pome fruit (apples and pears) worldwide, posing challenges due to the decrease in registered insecticides, rising resistance, and a changing climate. The larvae of the codling moth invade fruits and bore into the core, leaving brown-coloured holes that make fruits unmarketable. Biological control methods such as mating disruption with pheromones and granulovirus treatments are increasingly used to control this pest. Phenological models have been considered by many researchers as an important tool to improve the sustainable control of codling moth. Although the number of prediction models is steadily growing, there are always concerns regarding their applicability under new conditions and different scenarios. In this study, we developed and validated a new phenological prediction model for C. pomonella that can reliably predict adult moth flights during the growing season in temperate European climate conditions. Because, in addition to temperature, rain and wind can also have a significant influence, especially if they occur at dusk, when flights normally take place, these climate parameters were also included in the construction of the model. For this purpose, tests were carried out under controlled conditions in a wind tunnel and a rain simulator. Based on the outcomes, parameters as a function of rainfall and wind speed could be fine-tuned with respect to flight (and mating) behaviour. The validation showed good agreement of model predictions on the relative abundance of first- and second-generation moths. The outcomes of the field validation trials are presented and discussed, providing valuable insights into model-based sustainable control management of codling moth.

Keywords: Phenological prediction model, rain, wind, *Cydia pomonella*

Introduction

In our (Northwestern Europe) climatological conditions, codling moth typically has a very long irregular 1st generation flight (G1) and a smaller incomplete 2nd generation flight (G2). Because of the prolonged and unpredictable nature of the G1 flight, identifying peak activity periods is exceptionally difficult. Currently, growers must perform manual trap inspections twice a week to track flight activity; however, this process is highly labour-intensive and time-consuming. To address this challenge, in 2024 we developed a prediction model, using over 40 years of codling moth (*C. pomonella*) trap-catch records from the pcfruit monitoring network (covering ±20 locations across Belgium) (Belien et al., 2025). The dataset was fitted using the three-parameter non-linear regression model for first and second generation flight (G1–G2) as described by Damos et al. (2018). All analyses were performed in R (R Core Team, 2023). The optimized model parameters were subsequently implemented in an R script that uses hourly temperature data to predict flight activity throughout the growing season.

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However, evaluations showed that predictions based solely on this temperature-driven model often indicated a continuous, long-term risk period for flight, mating, and egg-laying. In contrast, real-world trap data revealed distinct intervals of reduced activity within those windows. Therefore, the purpose of the current study was to improve the model's precision by incorporating rain and wind as additional weather variables, aiming to better reflect the fluctuations observed in actual field conditions.

Material and Methods

Laboratory trials were carried out to assess the influence of rainfall on the behaviour of adult *C. pomonella* moths. Experiments were conducted in insect cages in a climate chamber set at 22–20 °C (day–night), 55% RH, with a programmed 24-h light cycle consisting of 1 h daylight, 2 h dusk, 3 h night, 2 h dawn, and 16 h daylight. Twilight periods (dusk and dawn) were set at 10% light intensity, and for these periods there were two separate conditions: simulated rain and no-rain control. Rainfall was simulated using a rain-generation system equipped with an Albuz nozzle operated at 3 bar (NAF), delivering a rainfall rate of 5.98 L h^{-1}. Adult male moths were released into the test arena 1 h before the onset of dusk at one side of the cage, with female moths or a *C. pomonella* pheromone dispenser at the other side of the cage, and the rain simulator between them. Each trial included separate tests with in total 25–30 male moths and 30 virgin females (or a pheromone dispenser instead of the female moths). Male moth activity was recorded at eight observation timings per trial, with registrations taken every 5 minutes over a 1-h observation window. Moth activity was scored binarily: 1 for flying or moving and 0 for remaining stationary. Similar trials were conducted to assess the influence of wind on moth behaviour. A custom wind tunnel was used, consisting of an aluminium frame 200 cm long and 90 cm wide and high. Airflow was generated by an adjustable front-mounted fan and calibrated using a Deuta anemometer. Male moths were released at one end of the tunnel, and their flight behaviour toward females positioned at the opposite end was observed under four wind speeds (1.0, 1.5, 2.0, and 3.0 m s^{-1}).

The data were checked for normality per test using the Shapiro-Wilk test. Depending on whether the distribution of the datasets was normal or non-normal, the results were further analysed by performing paired t-tests or Wilcoxon tests, respectively.

Results and Discussion

This rain test laboratory design allowed comparison of behavioural responses of *C. pomonella* moths with and without rainfall during twilight periods. Based on the results shown in Figure 1 it is clear that codling moths are mainly active during dusk, but when it rains their flight activity almost completely disappears. Moreover, they show little to no compensatory flight activity during subsequent dry periods. Regarding the results of the wind tunnel tests (not shown here), there is a decrease in flight activity as a function of wind speed, with almost no activity at wind speeds of 2 m s^{-1} or higher. Based on these outcomes, two additional variables (hourly rainfall and wind data) were added to the model script so that on days with rain and/or strong winds during dusk, the predicted flight activity (and risk of mating) is reduced. The resulting model script was used to predict the codling moth flight activity in apple orchards in Sint-Truiden in 2024 based on (hourly) data (temperature, rain, wind) of a local weather station. In these orchards codling moth was also monitored with pheromone trap (5 traps equipped with a Combo lure). As shown in Figure 2, the observed flight activity corresponds fairly well with the predicted flight activity, with the highest peak around 8 July.

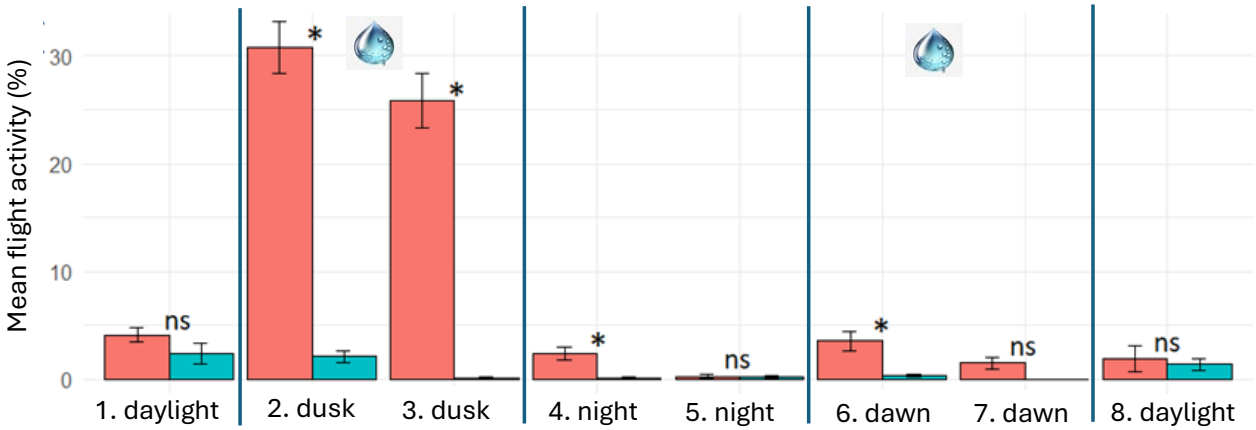

Figure 1: Results of the laboratory trial cage trials testing behavioural responses of *C. pomonella* moths. Red and blue bars display the observed flight activity during the 8 subsequent time periods of the simulated day, whereby rain (blue) did or did not (orange) occur only during the dusk and dawn periods (indicated by the raindrop). Significant differences are indicated with * (ns: not statistically significant).

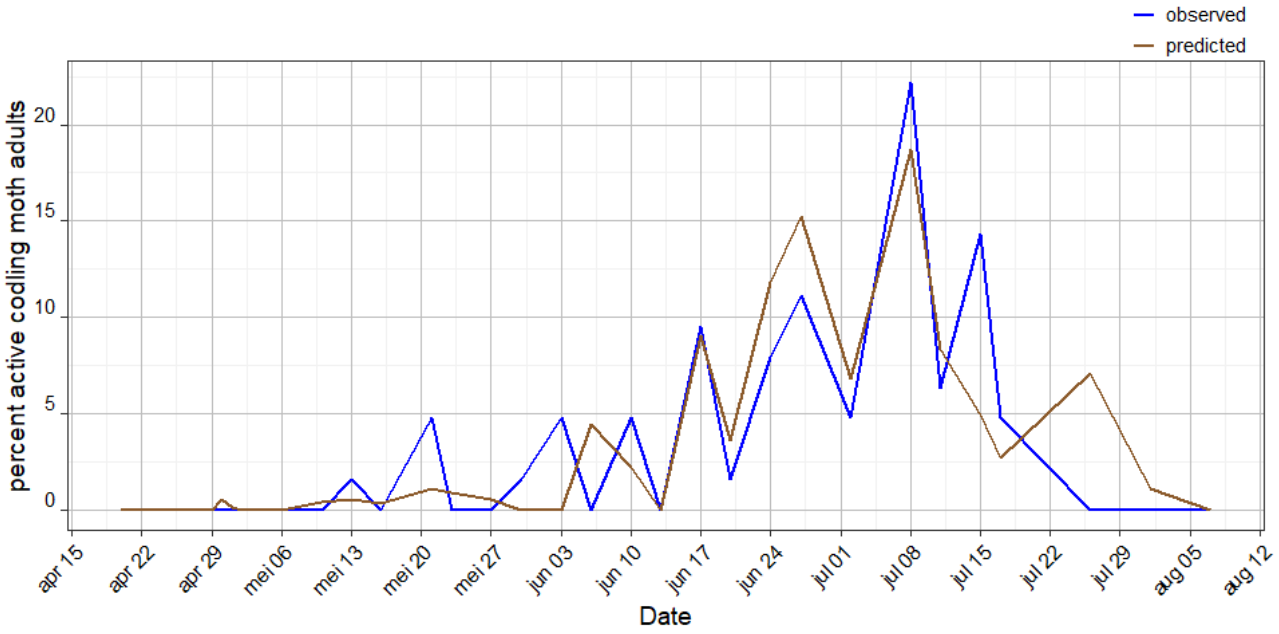

Figure 2: Observed flight activity (blue line: mean numbers of 5 pheromone traps in 5 orchards expressed as a percentage of the total number (caught in the monitoring traps) over the season) compared to the flight activity predicted by the model (brown line).

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