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Degree-day based phenological forecasting model of saddle gall midge (*Haplodiplosis marginata*) (Diptera: Cecidomyiidae) emergence

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ABSTRACT

Outbreaks of saddle gall midge (*Haplodiplosis marginata*) affecting wheat and other cereals are difficult to anticipate and may not be identified until damage has occurred. Earlier work on this pest has shown that degree day models can be used to predict *H. marginata* emergence based on soil temperatures. Here, we show how the availability of regular long-term trapping data can be used to update and improve upon this earlier model by predicting the progression of emergence. The emergence of adult *H. marginata* at three sites in the UK was monitored over two flight seasons using pheromone traps. The data confirmed the presence of multiple peaks in emergence over several weeks. Rainfall events followed by an accumulation of 512DD (±9.11DD) above 0 °C could be used to predict peaks with greater accuracy than degree day accumulations alone. Cumulative percentage emergence as a function of degree day accumulations was best described by a probit model. The probit model predicted *H. marginata* emergence at other sites and years to within 4 days. Application of these models will enable growers to forecast peaks in emergence, make informed assessments of crop risk and time application of chemical controls appropriately and only where required.

1. Introduction

Saddle gall midge, *Haplodiplosis marginata*, (von Roser) is an occasional pest of cereals across Europe. The larval stage of this insect is phytophagous, causing the formation of saddle-shaped depressions (galls) on the stems of host plants (Rowley et al., 2016). Crops most at risk are spring wheat and spring barley (Skuhravý et al., 1983, 1993), but the insect will also damage winter wheat and barley (Pope and Ellis, 2013). Damaged plants can exhibit a loss in yield due to shrunken grains as a consequence of galls disrupting the flow of nutrients to the ear (Woodville, 1968; Golightly, 1979). Stem breakage and secondary attack from pathogens at the site of the gall can also occur (Nijveldt and Hulshoff, 1968; Golightly and Woodville, 1974; Gratwick, 1992; Skuhravý et al., 1993). Following a resurgence of *H. marginata* outbreaks in several European countries from 2010 onwards, attempts have been made to consolidate and extend current knowledge of this insect to better inform pest management options (Censier et al., 2015; Rowley et al., 2016). Such reviews have highlighted the lack of information concerning *H. marginata* development and life cycle events. *Haplodiplosis marginata* populations can fluctuate wildly on a yearly basis, making outbreaks difficult to anticipate (Woodville, 1973; Basedow, 1986). Larvae may remain in a period of extended diapause for at least six years (Nijveldt and Hulshoff, 1968) and have been observed to form cocoons in response to drought (Censier et al., 2014a). The exact causes of diapause termination in this species are currently unknown, however the importance of both temperature and moisture has previously been highlighted (Skuhravý et al., 1983; Gratwick, 1992). Adult midges generally begin to emerge between the end of April and early May (Censier et al., 2015; Rowley et al., 2016), however early stages of infestation are seldom recognised due to the inconspicuous nature of the midge (Harris and Foster, 1999). Once damage is evident, chemical control applications are often unsuccessful as the larvae are protected by the leaf sheath (Gratwick, 1992). The use of reliable monitoring and forecasting tools are therefore critical in effective management of this pest (Censier et al., 2015).

The sex pheromone of *H. marginata* has been identified as 2-nonyl butyrate (Censier et al., 2014b) which has led to the development of species specific pheromone traps (Censier et al., 2016; Rowley et al., 2017). This advance has made it possible to reliably monitor the emergence and flight activity, providing opportunity to

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easily study populations in the field (Censier et al., 2016). In pest management, pheromone monitoring can be used to time chemical controls appropriately (Witzgall et al., 2010). The traps, however only provide a limited amount of advanced warning of insect activity and cannot predict the peaks in emergence which have been observed previously in this species (Censier et al., 2016). In addition, traps can be difficult to maintain consistently over an entire flight season and give no indication as to the duration of emergence. Phenological forecasting is a tool used in pest management to predict insect emergence and activity by modelling the progression of a particular developmental stage in relation to environmental variables (Prasad and Prabhakar, 2012). Such models can be used to support pheromone monitoring, by predicting when to deploy traps and identifying periods of peak activity on a year-to-year basis. Successful forecasting models have so far been developed for other pest Cecidomyiidae such as orange wheat blossom midge *Sitodiplosis mosellana* (Géhin) (Elliott et al., 2009; Jacquemin et al., 2014); swede midge *Contarinia nasturtii* (Keiffer) (Hallett et al., 2007); sorghum midge *Contarinia sorghicola* (Coquillett) (Baxendale et al., 1984); blueberry gall midge *Dasineura oxycoccana* (Johnson) (Hahn and Isaacs, 2012); and pine needle gall midge *Thecodiplosis japonensis* (Uchida et Inouye) (Son et al., 2007). When combined with meteorological data, models can provide assessments of crop risk over a wide geographical area and prompt farmers to inspect crops or deploy monitoring traps (Prasad and Prabhakar, 2012). Outputs from models may also feed into more complex decision support systems to guide farmers on when to employ pest management strategies (Strand, 2000).

An earlier degree day based model of the development of *H. marginata* in the soil stage successfully predicted onset of emergence of the insect to within 4 days at the sites tested (Rowley et al., 2016). Soil moisture has previously been identified as being important in *H. marginata* emergence (Skuhravý et al., 1983) and here, we attempt to expand upon the earlier model by identifying the role of rainfall in the phenology of this insect. Additionally, intensive sampling of *H. marginata* populations using pheromone traps has enabled the development of a model to describe the cumulative percentage emergence of the insect over the flight season. These models not only improve upon the previously published version by predicting cumulative percentage emergence over the flight season, but can also be used to forecast periods of peak *H. marginata* emergence and provide a much more comprehensive understanding of the development of this insect in the soil stage.

2. Materials and methods

2.1. Field data

Haplodiplosis marginata activity was monitored at three sites in the UK: Buckinghamshire (Bucks) and Oxfordshire (Oxon) in 2015 and 2016, and Wiltshire (Wilts) in 2016. Pheromone traps were placed in two fields at each site. All fields were in wheat with the exception of one field at Bucks in 2015 which was in field beans and one field at Oxon in 2016 which was in oilseed rape. Four pheromone traps per field were arranged in transects perpendicular to the field edge, at least 40 m into the crop with a distance of 20 m between traps. Pheromone traps consisted of a standard red delta trap with a removable sticky insert (Agralan Ltd, Ashton Keynes, UK) hung on a fibreglass cane. Pheromone lures comprised a polyethylene vial containing 0.5 mg (*R*)-2-nonyl butyrate placed in the centre of the trap (Natural Resources Institute, University of Greenwich). The trapping period began approximately a week prior to the start of the flight season (mid-April to May) and sticky cards were changed every 3–4 days for 8 weeks, after which they were changed weekly until emergence ceased. The same pheromone lures were used throughout the field season. Numbers of *H. marginata* caught at each trapping interval were counted. Hourly soil temperatures and rainfall were obtained from the UK Meteorological Office MIDAS network based on readings from weather stations that were less than 20 km from each site (Met Office, 2012).

2.2. Modelling peaks in emergence

Two degree day models were developed to attempt to describe *H. marginata* emergence patterns. Peaks in *H. marginata* activity were identified from catch numbers and the start and end dates were approximated as occurring midway between counts. The first model assumed a straightforward relationship between degree day accumulations from a single date of biofix to the start of each peak (Fig. 1a). Here, different DD accumulations do not represent exact physiological requirements but are used to approximate the time to emergence for groups of insects experiencing different temperatures lower down the soil profile. The second model (Fig. 1b) assumed equal DD accumulations between each rainfall event and the subsequent peak, as described by Jacquemin et al. (2014) from observations of *S. mosellana* emergence.

The same biofix was used as the start of DD accumulations for both models, defined as the date of first rainfall on or after 1st March. Here, biofix represents the time when conditions were suitable for pupation to occur post-diapause. The chosen biofix assumes the diapause requirements for *H. marginata* would have been met prior to 1st March, with little or no post-diapause development. It also assumes moisture is necessary for pupation to occur, as with previous models of *H. marginata* and *S. mosellana* development (Oakley et al., 1998; Elliott et al., 2009; Rowley et al., 2016). Degree day (DD) accumulations were calculated above 0 °C from hourly temperature data as described in Rowley et al. (2016). Mean hourly temperatures above 0 °C were summed for each day and then divided by 24 to give degree days (Cesaraccio et al., 2001).

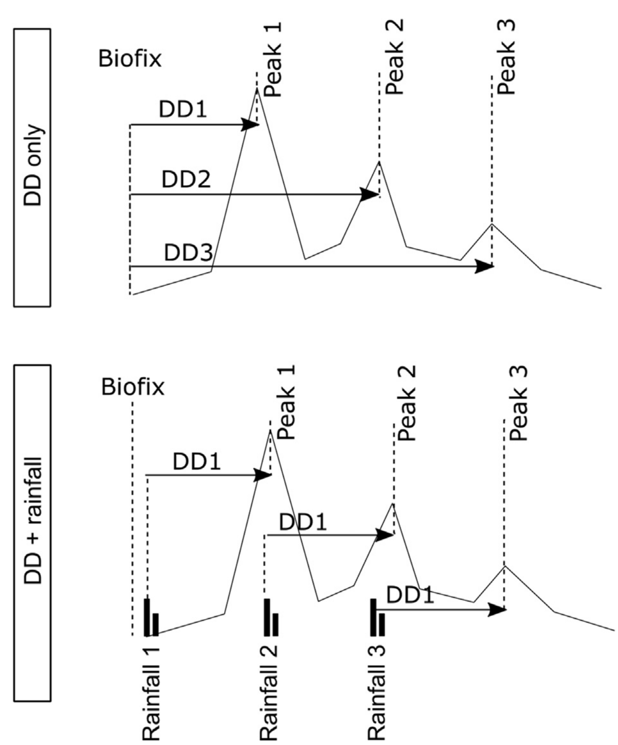

Fig. 1. Representation of two different *Haplodiplosis marginata* emergence models. DD refers to degree day accumulations with numbers indicating unique DD values.