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

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1 **Degree-day based phenological forecasting model of saddle gall midge (*Haplodiplosis marginata*)**

2 **(Diptera: Cecidomyiidae) emergence**

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8

10 **Abstract**

11 Outbreaks of saddle gall midge (*Haplodiplosis marginata*) affecting wheat and other cereals are

12 difficult to anticipate and may not be identified until damage has occurred. Earlier work on this pest

13 has shown that degree day models can be used to predict *H. marginata* emergence based on soil

14 temperatures. Here, we show how the availability of regular long-term trapping data can be used to

15 update and improve upon this earlier model by predicting the progression of emergence. The

16 emergence of adult *H. marginata* at three sites in the UK was monitored over two flight seasons using

17 pheromone traps. The data confirmed the presence of multiple peaks in emergence over several

18 weeks. Rainfall events followed by an accumulation of 512DD (±9.11DD) above 0 °C could be used to

19 predict peaks with greater accuracy than degree day accumulations alone. Cumulative percentage

20 emergence as a function of degree day accumulations was best described by a probit model. The

21 probit model predicted *H. marginata* emergence at other sites and years to within 4 days. Application

22 of these models will enable growers to forecast peaks in emergence, make informed assessments of

23 crop risk and time application of chemical controls appropriately and only where required.

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25

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; Skuhravý et al., 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).

50   The sex pheromone of *H. marginata* has been identified as 2-nonyl butyrate (Censier et al., 2014b)

51   which has led to the development of species specific pheromone traps (Censier et al. 2016, Rowley et

52   al., 2017). This advance has made it possible to reliably monitor the emergence and flight activity,

53   providing opportunity to easily study populations in the field (Censier et al., 2016).   In pest

54   management, pheromone monitoring can be used to time chemical controls appropriately (Witzgall

55   et al., 2010). The traps, however only provide a limited amount of advanced warning of insect activity

56   and cannot predict the peaks in emergence which have been observed previously in this species

57   (Censier et al., 2016). In addition, traps can be difficult to maintain consistently over an entire flight

58   season and give no indication as to the duration of emergence. Phenological forecasting is a tool used

59   in pest management to predict insect emergence and activity by modelling the progression of a

60   particular developmental stage in relation to environmental variables (Prasad and Prabhakar, 2012).

61   Such models can be used to support pheromone monitoring, by predicting when to deploy traps and

62   identifying periods of peak activity on a year-to-year basis. Successful forecasting models have so far

63   been developed for other pest Cecidomyiidae such as orange wheat blossom midge *Sitodiplosis*

64   *mosellana* (Géhin) (Elliot et al., 2009; Jacquemin et al., 2014); swede midge *Contarinia nasturtii*

65   (Keiffer) (Hallett et al., 2007); sorghum midge *Contarinia sorghicola* (Coquillett) (Baxendale et al.,

66   1984); blueberry gall midge *Dasineura oxycoccana* (Johnson) (Hahn and Isaacs, 2002); and pine needle

67   gall midge *Thecodiplosis japonensis* (Uchida et Inouye) (Son et al. 2007).   When combined with

68   meteorological data, models can provide assessments of crop risk over a wide geographical area and

69   prompt farmers to inspect crops or deploy monitoring traps (Prasad and Prabhakar, 2012). Outputs

70   from models may also feed into more complex decision support systems to guide farmers on when to

71   employ pest management strategies (Strand, 2000).

72   An earlier degree day based model of the development of *H. marginata* in the soil stage successfully

73   predicted onset of emergence of the insect to within 4 days at the sites tested (Rowley et al., 2016).

74   Soil moisture has previously been identified as being important in *H. marginata* emergence (Skuhravý

75   et al., 1983) and here, we attempt to expand upon the earlier model by identifying the role of rainfall

76   in the phenology of this insect. Additionally, intensive sampling of *H. marginat*a populations using

77 pheromone traps has enabled the development of a model to describe the cumulative percentage

78 emergence of the insect over the flight season. These models not only improve upon the previously

79 published version by predicting cumulative percentage emergence over the flight season, but can also

80 be used to forecast periods of peak *H. marginata* emergence and provide a much more comprehensive

81 understanding of the development of this insect in the soil stage.

82

83 **2. Materials and Methods**

84 *2.1 Field data*

85 *Haplodiplosis marginata* activity was monitored at three sites in the UK: Buckinghamshire (Bucks) and

86 Oxfordshire (Oxon) in 2015 and 2016, and Wiltshire (Wilts) in 2016. Pheromone traps were placed in

87 two fields at each site. All fields were in wheat with the exception of one field at Bucks in 2015 which

88 was in field beans and one field at Oxon in 2016 which was in oilseed rape. Four pheromone traps per

89 field were arranged in transects perpendicular to the field edge, at least 40 m into the crop with a

90 distance of 20 m between traps. Pheromone traps consisted of a standard red delta trap with a

91 removable sticky insert (Agralan Ltd, Ashton Keynes, UK) hung on a fibreglass cane. Pheromone lures

92 comprised a polyethylene vial containing 0.5mg (*R*)-2-nonyl butyrate placed in the centre of the trap

93 (Natural Resources Institute, University of Greenwich). The trapping period began approximately a

94 week prior to the start of the flight season (mid-April to May) and sticky cards were changed every 3-

95 4 days for 8 weeks, after which they were changed weekly until emergence ceased. The same

96 pheromone lures were used throughout the field season. Numbers of *H. marginata* caught at each

97 trapping interval were counted. Hourly soil temperatures and rainfall were obtained from the UK

98 Meteorological Office MIDAS network based on readings from weather stations that were less than

99 20km from each site (Met Office, 2012).

100 *2.2 Modelling peaks in emergence*

101   Two degree day models were developed to attempt to describe *H. marginata* emergence patterns.

102   Peaks in *H. marginata* activity were identified from catch numbers and the start and end dates were

103   approximated as occurring midway between counts. The first model assumed a straightforward

104   relationship between degree day accumulations from a single date of biofix to the start of each peak

105   (Fig 1a). Here, different DD accumulations do not represent exact physiological requirements but are

106   used to approximate the time to emergence for groups of insects experiencing different temperatures

107   lower down the soil profile. The second model (Fig 1b) assumed equal DD accumulations between

108   each rainfall event and the subsequent peak, as described by Jacquemin et al. (2014) from

109   observations of *S. mosellana* emergence.

110   The same biofix was used as the start of DD accumulations for both models, defined as the date of

111   first rainfall on or after 1st March. Here, biofix represents the time when conditions were suitable for

112   pupation to occur post-diapause. The chosen biofix assumes the diapause requirements for *H.*

113   *marginata* would have been met prior to 1st March, with little or no post-diapause development. It

114   also assumes moisture is necessary for pupation to occur, as with previous models of *H. marginata*

115   and *S. mosellana* development (Oakley et al., 1998; Elliot et al., 2009; Rowley et al., 2016). Degree

116   day (DD) accumulations were calculated above 0°C from hourly temperature data as described in

117   Rowley et al. (2016). Mean hourly temperatures above 0°C were summed for each day and then

118   divided by 24 to give degree days (Cesaraccio *et al.*, 2001). Rainfall events were classified as daily

119   rainfall over 1 mm following 3 days without precipitation. The threshold of 1 mm was used to account

120   for inaccuracies in monitoring equipment. For both models, the coefficient of variation of DD

121   accumulations was calculated for all sites and years.

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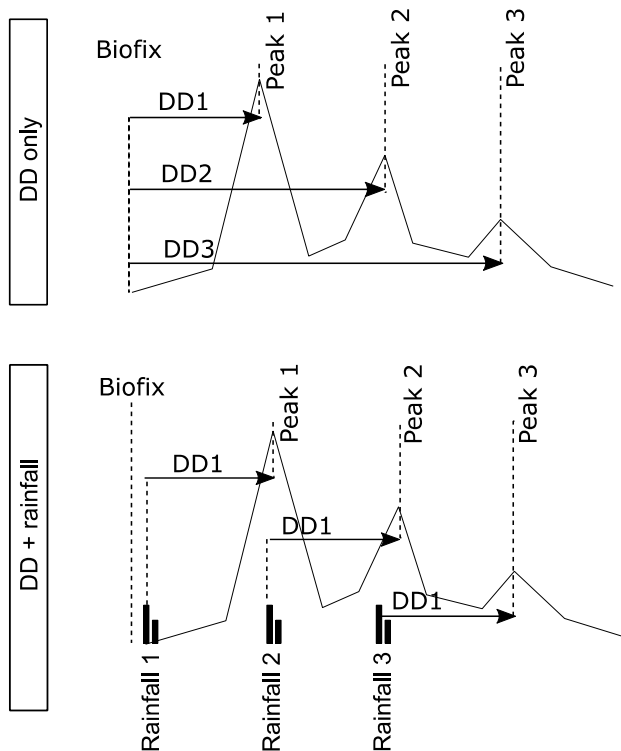
Figure 1. Representation of two different *Haplodiplosis marginata* emergence models. DD refers to

degree day accumulations with numbers indicating unique DD values.

2.3 Percentage emergence model

Pooled field data for each site were used to calculate the cumulative percentage emergence for the

entire flight period at each monitoring date. Monitoring dates were converted to degree days

calculated from the predetermined date of biofix for each site and year, as described in section 2.2.

Three regression models were tested to best describe the relationship between degree days and

cumulative percentage emergence, all having previously been used successfully to describe insect

development in response to time or temperature. A two-parameter Weibull function was fitted using

nonlinear least squares regression:

$$y = 100(1 - \exp(-(x/\alpha)^{\beta})$$

Where y is the cumulative percentage emergence, x is cumulative degree days and α and β are model

parameters. Two generalised linear models were also performed with binomial errors and logit or

probit links (Forrest and Thomson, 2011). Model selection was done by comparing the adjusted r-

squared and root mean square error (RMSE) values of models fitted to observed data (Damos et al.,

138   2010; Parker et al., 2011). The chosen model was validated against other sites and years for which

139   the date of *H. marginata* emergence is known but which were not included in model development.

140   All statistical analyses were done in R-3.2.2 (R Core Team, 2015).

141

142   **3. Results and Analysis**

143   3.1 *Modelling peaks in emergence*

144   Emergence began no later than 2nd May (± 3 days) at all study sites and continued until as late as mid-

145   July. Total site catches ranged from 1,755 to 20,384 individuals over the entire flight season. The

146   catch data revealed apparent 'waves' of emergence of *H. marginata* over time, with a maximum catch

147   rate of 200 individuals per trap per day. The first peak generally occurred soon after the initial

148   emergence, with smaller subsequent peaks occurring at two- to three-week intervals. At the two sites

149   for which data were obtained in both years, mean soil temperatures in April and May 2015 varied by

150   only 2.33 °C whereas in 2016 the difference rose to 5.56 °C, reflecting a cooler April and warmer May

151   than the previous year. Mean daily rainfall at the two sites was higher in 2016, averaging 2.28 mm

152   compared with 1.31 mm in 2015. The maximum daily rainfall of 33.8 mm occurred in 2016 at the

153   Oxon site.

154   The DD-only model showed an average accumulation of 528.25DD (± 7.69DD) between the biofix and

155   the onset of emergence. Accumulations between the biofix and subsequent peaks however were

156   more variable, averaging 796.82DD (± 39.14DD) and 1083.68 (± 54.81DD) for peaks 2 and 3

157   respectively (Table 1). Across all sites and years, 14 out of 29 identified rainfall events could be linked

158   to the beginning of peaks in emergence (Fig. 2). Subsequent rainfall events however, may have

159   additionally contributed to increased emergence over the duration of the peak as represented by the

160   shaded areas of Figure 2. The DD + rainfall model showed an average accumulation of 512.42DD (±

161   9.11DD) between a triggering rainfall event and a subsequent peak in emergence activity (Table 1, Fig.

162   2).

163

164   Table 1. Degree day accumulations for the periods between biofix and emergence peaks (DD only

165   model) and the periods between inductive rainfall events and emergence peaks (DD + rainfall

166   model), calculated for each site and year. Mean, standard deviation (SD) and coefficient of variation

167   (CV) values were calculated from the DD values for each peak separately for both models. Mean DD

168   for all peaks was additionally calculated for the DD + rainfall model.

|	DD only 1: Biofix - Peak			DD + rainfall : Rain – Peak		
	Peak 1 (DD1)	Peak 2 (DD2)	Peak 3 (DD3)	Peak 1 (DD1)	Peak 2 (DD1)	Peak 3 (DD1)
2015						
Bicester (Oxon)	537.24	764.91	1158.41	537.24	466.13	461.45
H. Wycombe (Bucks)	563.62	1054.46	1339.97	563.62	477.97	560.78
2016						
Bicester (Oxon)	484.68	746.86	-	484.68	551.44	-
H. Wycombe (Bucks)	534.13	694.30	926.43	534.13	486.59	516.16
Devizes (Wilts)	521.56	723.57	909.91	521.56	504.43	507.65
Mean	528.25	796.82	1083.68	528.25	497.31	511.51
SD	28.77	146.43	205.10	28.77	33.32	40.7
CV	**0.054**	**0.184**	**0.189**	**0.054**	**0.067**	**0.079**
					Mean (all peaks) (±SEM)	**512.42 (± 9.11)**

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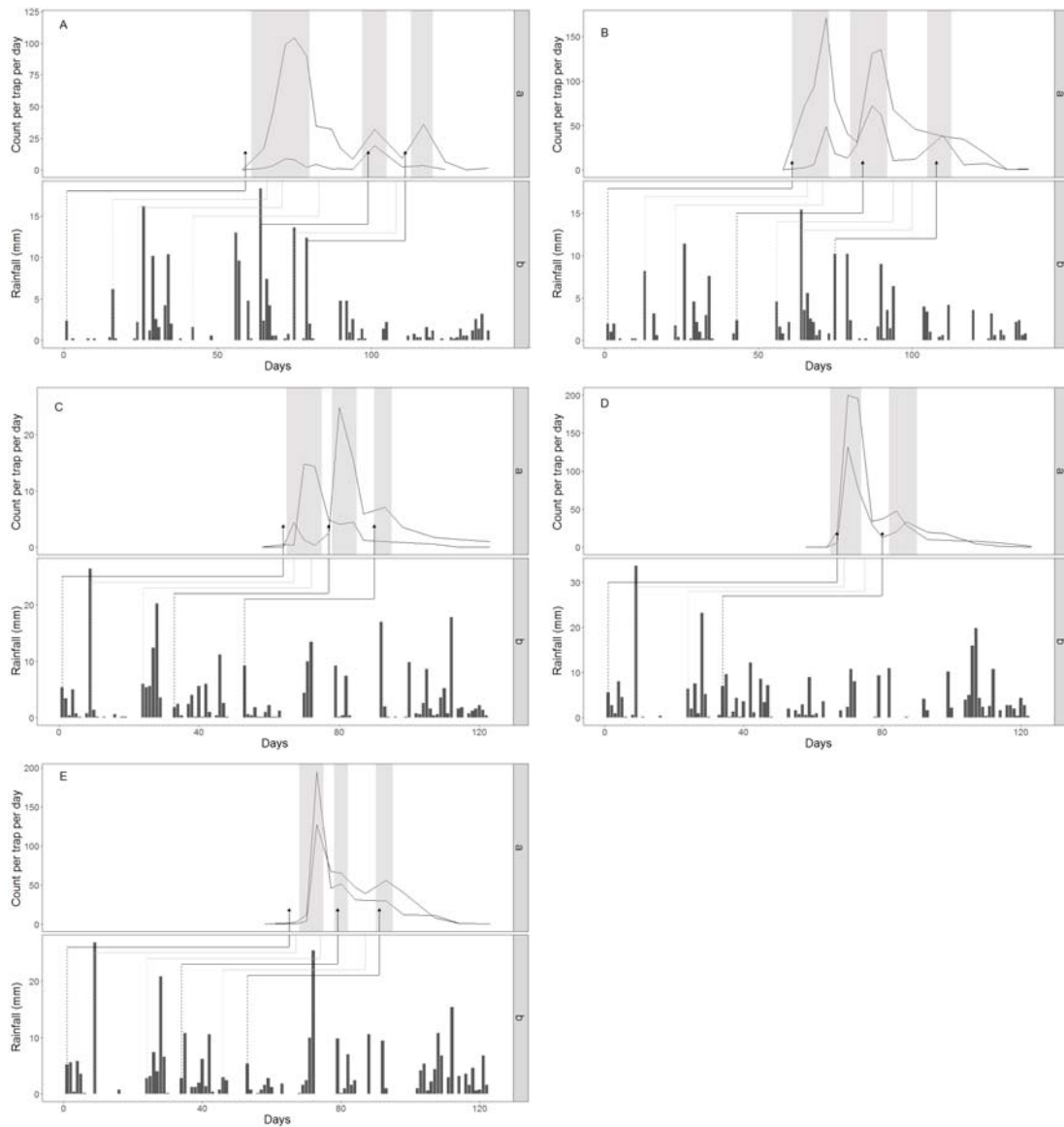
Figure 2. *Haplodiplosis marginata* catch per trap per day (panel a) and 24hr rainfall in mm (panel b)

for each day of the trapping period. Black arrows represent inductive rainfall events, grey lines

indicate non-inductive rainfall events. Horizontal lines represent degree day accumulations of 512

DD. Shading represents identified periods of peak emergence with the start and end dates

approximated to the midpoint of trapping intervals. A) Bucks 2015, B) Oxon 2015, C) Bucks 2016, D)

Oxon 2016, E) Wilts 2016

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187

188   3.2 *Percentage emergence model*

189   The Weibull model was the best fitting model based on the adjusted r-squared value, accounting for

190   91% of the variation in the data. The GLM with probit link had the lowest RSME values (Table 2).

191   Generation of the models showed that the Weibull model had a poor fit at the lower end of the data

192   however, suggesting that it would be a poor predictor of the start of H. marginata emergence (Fig. 3).

193   The probit model was therefore selected for validation and predicted that 10% emergence of *H.*

194   *marginata* would occur at 550DD post-biofix. When validated against other sites and years, the probit

195   model agreed with the observed date of emergence to within a maximum of 4 days (± 4 days), with

196   the error reflecting uncertainty in the true emergence date as a result of the sampling interval (Table

197   3).

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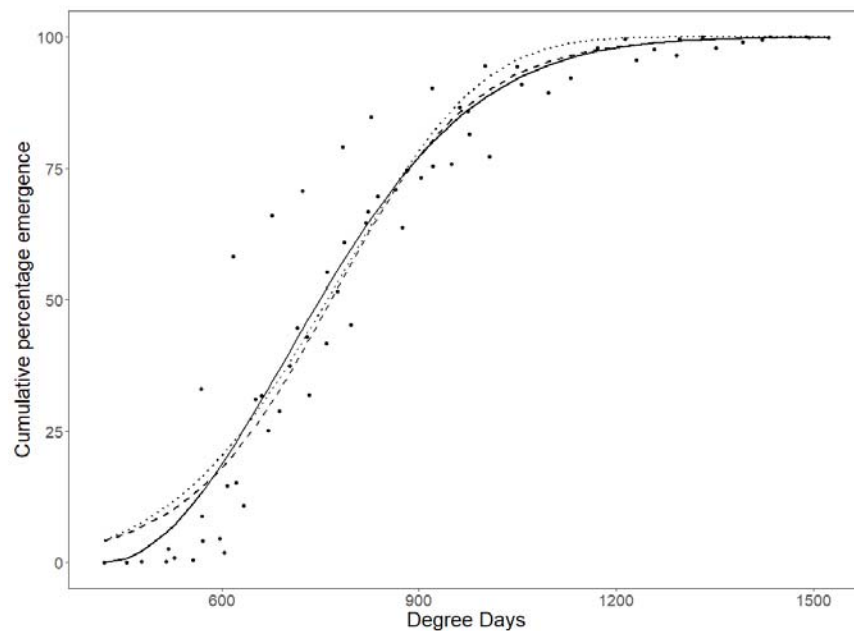
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200   Figure 3. Percentage cumulative emergence of *Haplodiplosis marginata* as a function of accumulated

201   degree days from biofix for all sites and years studied. Predicted emergence based on the probit

202   model (solid line), weibull model (dotted line) and binomial GLM (dashed line) shown.

203

204 Table 2. Parameter estimates and standard error (SE) for all models. RMSE and adjusted R^2 values

205 shown. Predicted DD accumulations required for 10%, 50% and 90% based on the selected model.

Model	Parameter	Est. value	SE	P-value	RMSE	Adj. R²	Model predictions	
Binomial GLM	α	7.126	0.01616	<0.001	10.03	0.89		
	β	-47.16	0.10725	<0.001				
Weibull	α	822.061	10.6095	<0.001	10.67	0.91		
	β	4.696	0.3915	<0.001				
Probit model	α	4.124	0.00845	<0.001	9.98	0.89	10%	550.04
	β	-27.308	0.05616	<0.001			50%	750.47
							90%	1023.93

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207

208 Table 3. Observed and predicted 10% emergence dates for probit model for other sites and years, data

209 from which were not used in model development. Differences in days between observed and

210 predicted dates shown. Error in brackets represents uncertainty in emergence dates which are given

211 as a midpoint between sampling dates.

		Probit Model	
Site	Observed emergence date	Predicted emergence date	Days difference (Obs – Pred)
2014			
Royston (Herts)	30th April (± 0 days)	27th April	3
Bicester (Oxon)	3rd May (± 3.5 days)	30th April	3
H. Wycombe (Bucks)	3rd May (± 3.5 days)	30th April	3
Aylesbury (Bucks)	3rd May (± 3.5 days)	2nd May	1
2015			
Royston (Herts)	2nd May (± 2 days)	1st May	1
Aylesbury (Bucks)	9th May (± 4 days)	5th May	4
Glemsford (Suffolk)	3rd May (± 3 days)	2nd May	1
Thirsk (N. Yorks)	9th May (± 2 days)	9th May	0
Devizes (Wiltshire)	3rd May (± 3 days)	30th April	3
2016			
Glemsford (Suffolk)	5th May (± 3 days)	6th May	-1
Max. difference			**4 (± 4days)**
SD (Obs - Pred)			**1.93**

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4. Discussion

The work presented here clearly demonstrates how rainfall and soil temperature can be used to develop forecasts of *H. marginata* emergence. The association between soil temperature and moisture and the onset of emergence in this species has been made in earlier work (Rowley et al., 2016). With the availability of more detailed catch data, we have improved upon this earlier model to develop a cumulative emergence forecast for the entire flight season. Furthermore, we have confirmed the role of rainfall events in triggering *H. marginata* emergence, showing that moisture as well as temperature is crucial to the post-diapause development of this insect.

Moisture is an important but often underappreciated aspect of insect phenology and development (Tauber and Tauber, 1976; Tauber et al, 1998). Rainfall is reported to be important in the emergence of a number of Cecidomyiidae species such as Hessian fly *Mayetiola destructor* (Say) (Woli et al., 2014), swede midge (Chen et al., 2011) and apple leaf curling midge *Dasineura mali* (Kieffer) (Cross et al., 2009) and in the case of the latter acts to increase the number of suitable oviposition sites by increasing the rate of host plant growth (Cross et al., 2009). The incorporation of soil moisture or rainfall into a degree day-based phenological model can lead to improved precision in some species (e.g. Baxendale and Teetes, 1983; Baxendale et al., 1984; Tauber et al., 1994). Early attempts to model the emergence pattern of orange wheat blossom midge, *S. mosellana,* recognised the importance of soil moisture in pupation and therefore emergence (Basedow, 1977; Basedow and Gillich, 1982; Oakley et al., 1998; Elliot et al., 2009). It was not until this insect was studied under controlled conditions and with more frequent field sampling that rainfall events could be linked to the inducement of this final stage of development (Jacquemin et al., 2014). Here, we show a similar effect of rainfall on *H. marginata* emergence based on field data. The onset of a precipitation period followed by the accumulation of 512DD above 0 °C predicted an increase in *H. marginata* emergence to within 3 days of the midpoint of the observed peaks. Just under 50% of all rainfall events were found to be inductive. The model proposed here and that proposed by Jacquemin et al., (2014) agree with theories of insect development which state that post-diapause, insects can remain in a state of

240   'readiness' until an environmental cue triggers the onset of pupation (Tauber and Tauber, 1976;

241   Hodek, 1996; Koštál, 2006). Such a mechanism ensures that development typically resumes when

242   conditions are favourable regardless of when diapause is terminated. If no cue is received, the insect

243   recommences diapause for another year (Tauber and Tauber, 1976). This would account for the

244   proportion of *S. mosellana* and *H. marginata* larvae that undergo extended diapause (Nijveldt and

245   Hulshoff, 1968; Basedow, 1977), which is thought to be up to twelve years in the case of *S. mosellana*

246   (Barnes, 1952). Not all rainfall events were directly linked to increased catch rates but smaller peaks

247   in emergence may have been overlooked at the trapping interval used or due to weather conditions

248   affecting the catch rate on particular days. Additionally, many rainfall events while not initiating peaks

249   in emergence may still have contributed to the high numbers of insects being caught during the

250   trapping interval (Fig. 2). Soil conditions in the preceding days might also determine the impact of a

251   particular rainfall event. Factors such as landscape, soil type and structure will affect the permeability

252   and moisture retention of soil, and thus the impact of any one rainfall event. Soil type however, was

253   not found to be of significance in the emergence of swede midge, when investigated alongside soil

254   moisture (Chen and Shelton, 2007). In their studies on sorghum midge, Baxendale *et al*. (1983, 1984)

255   found that rainfall delayed emergence and drier years correlated with lower heat requirements. No

256   such pattern was observed here, the site with the earliest emergence (Oxon 2016) also experienced

257   43% more rain than the next wettest site in the four weeks prior to emergence. This site also had a

258   greater initial rate of emergence, resulting in only two clear emergence peaks rather than three (Fig.

259   2). This may have been due to the 33.8mm of rainfall which the site received on the 9th March,

260   resulting in a greater proportion of larvae encountering favourable pupation conditions at once. Due

261   to the trapping intervals used in this study and other factors affecting insect numbers over the flight

262   season, the relationship between rainfall amount and trap catch could not be determined. It may be

263   possible to examine this relationship under controlled conditions however, which could add additional

264   predictive value to the model described here.

265

266 Waves of emergence in *H. marginata* have been observed before from data collected using non-

267 specific traps (Censier et al., 2016). Such waves may arise because not all larvae encounter the

268 conditions necessary for pupation all at once, for example due to their depth in the soil. From an

269 ecological perspective, this strategy increases the chance of coincidence between newly emerged

270 adults and a suitable growth stage of the host plant. It is particularly relevant for *H. marginata*, which

271 has a short adult lifespan of only 1 - 7 days (Nijveldt and Hulshoff, 1968; Popov *et al.*, 1998). The

272 pheromone traps used here only captured adult males of *H. marginata*. As males tend to emerge 3 –

273 5 days before females (Skuhravý *et al.* 1983), the models described here based on male emergence

274 would give sufficient warning of female emergence for farmers to be able to check crops for evidence

275 of egg laying. The sex ratio of females to males has previously been reported by Skuhravý *et al.* (1983)

276 as 59:41 and 54:46 based on emergence trap and Möricke trap catches, respectively. The numbers of

277 males caught in these traps were therefore likely to be slightly lower than, or comparable with, the

278 number of females emerging.

279

280 The importance of the start date in calculating DD accumulations is widely recognised (Pruess, 1983)

281 and model accuracy can be improved if there is a biological basis for the date selected (e.g. Riedl et

282 al., 1976). This date is commonly referred to as the 'biofix'. Previous work on the development of *H.*

283 *marginata* proposed a point of biofix as the first rainfall event once mean daily soil temperatures rose

284 above 6 °C after the 1st March (Rowley et al., 2016). Now, with more comprehensive emergence data,

285 we propose simplifying the model to remove the temperature threshold. Laboratory observations of

286 *H. marginata* development suggest that pupation will proceed at 10 °C but not at 5 °C, therefore the

287 lower developmental threshold is likely to fall within this range (Baier, 1963; Nijveldt and Hulshoff,

288 1968). The 1st March is often selected as a start date for DD accumulations where there is a no lower

289 developmental threshold data to draw upon (Pruess, 1983), such as models of *S. mosellana* emergence

290 (Wise and Lamb, 2004; Elliot, 2009). The same date was used here based on a lack of observed *H.*

291 *marginata* development in the field prior to 1st March previously (Pope and Ellis, 2013), and the

292 assumption that earlier soil temperatures had little effect on *H. marginata* development as they were

293   at the lower end of the developmental threshold range. Photoperiodism can also play a major role in

294   the termination of insect diapause, which further validates removing the temperature threshold from

295   the biofix estimate (Tauber and Tauber, 1976; Saunders, 2014).

296

297   The DD-based cumulative emergence model proposed here for *H. marginata* predicted 10%

298   emergence would occur at 550 DD post-biofix and was accurate to within 4 days (± 4 days) when

299   validated against observations from other sites and years. The value for 10% emergence was deemed

300   to be an appropriate proxy for the start of emergence given the error involved in trapping insects at

301   very low densities; it is unlikely that the earliest onset of emergence will have been recorded

302   particularly in 2014 when pheromone traps were not available. The predictive capacity of the model

303   to within 4 days is on a par with the previously published DD emergence model (Rowley et al., 2016).

304   The advantage of the new model is the ability to predict cumulative emergence over the entire flight

305   season, rather than just the start date. This will enable the midpoint and conclusion of flight periods

306   to be estimated and aid in the assessment of the need for chemical controls or the effectiveness of

307   insecticides applied earlier in the emergence period. It may mean that pest management options can

308   be used more judiciously, so that chemical controls are only applied if the crop is at a vulnerable

309   growth stage prior to the mid-point of emergence. The model produced here relies on data collected

310   by a national network of weather stations. This means that forecasts can be made for different parts

311   of the country, providing estimates based on local weather conditions. Multiple pest forecast models

312   could be used to identify different periods of activity from the same meteorological data, for example

313   the VIPS automatic forecasting system developed in Norway (NIBIO, 2017) and the CIPRA model in

314   Quebec (Bourgeois et al., 2005). Ideally, such a forecasting system would be used alongside crop

315   growth forecasts to provide an assessment of crop risk throughout the flight period. Continued

316   application and evaluation of predictive models for *H. marginata* and other pest species will further

317   improve the reliability of such forecasts in the future.

318

319   **Acknowledgements**

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