Research Article

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Targeted control of the saddle gall midge, *Haplodiplosis marginata* (von Roser) (Diptera: Cecidomyiidae), and the benefits of good control of this pest to winter wheat yield[†]

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Abstract

BACKGROUND: Since 2010 there has been a resurgence of the saddle gall midge, *Haplodiplosis marginata* (von Roser), in Belgium and several other European countries, with this pest sometimes causing severe damage in cereals. In 2012 and 2013, field trials were conducted in heavily infested fields to assess its impact on winter wheat crops and to determine efficient ways of dealing with severe infestations.

RESULTS: Crop exposure to *H. marginata* varied with the different protection methods tried. These methods included 1–4 successive applications of lambda-cyhalothrin. Yield losses were significant, reaching 6% in 2012 and as high as 15% in 2013, and these losses were linearly related to the number of galls on stems.

CONCLUSION: The trials showed that insecticide applications needed to be synchronised with *H. marginata* flight peaks and to target the egg hatching period. They also revealed that insecticides applied to coincide with the first flight could, in humid conditions, also reach the larvae close to the soil surface, prior to their pupation.

Keywords: *Haplodiplosis marginata*; saddle gall midge; pest harmfulness; insecticide treatment; lambda-cyhalothrin; yield losses; winter wheat

1 INTRODUCTION

Since 2010 there has been a resurgence of the saddle gall midge, *Haplodiplosis marginata* (von Roser, 1840), in Belgium and several other European countries, including France, the Netherlands and the United Kingdom.[1,2] This small univoltine dipteran belonging to the Cecidomyiidae family is a major pest in Central Europe, but it is generally much less harmful in Western Europe.[3] In Belgium, the last outbreak occurred in the 1960s, and the insect was not then reported again for about 40 years.[4,5]

The saddle gall midge affects all cereals, except oats, which rarely suffer economic damage from this pest. Wheat is the most frequently attacked host plant.[5–7] In cereals, the imago usually emerges during stem elongation, between mid-April and the end of June. Generally, the adult lifespan does not exceed 5 days. Mating takes place almost immediately after emergence, and females lay eggs on the leaves a few hours later. After hatching, the larvae creep to the stem, where they feed under the leaf sheath, inducing the development of saddle-shaped galls, 5–10 mm long. Between mid-June and mid-July, the fully grown larvae leave the stems after rainfall and burrow into the soil, where they form cells within the soil and enter into diapause. In the following spring, most larvae move to the soil surface to pupate. Pupation lasts 14–25 days, after which the adults emerge.[4,7,8]

As females lay eggs preferentially on the youngest leaves of cereals, gall distribution on the stems reflects flight phenology. In the case of early flights, eggs are thus laid on the lower leaves of plants and larvae cause galls on the lower internodes, whereas with late flights the galls appear on the upper internodes.[9] Usually, a single larva develops in each gall and there are 2–3 galls per stem, but during outbreaks up to 60 larvae can develop on one stem.[3] Depending on the time and intensity of *H. marginata* attacks, gall development can lead to a decline in the number of fertile spikelets per ear and in grain number and quality; in extreme conditions it can completely inhibit spike formation.[4,6,7] Galls can

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also result in broken stems and the development of pathogens such as fungi and bacteria.[4,7]

In the 1960s and 1970s, a few studies were conducted to assess the damage impact of *H. marginata* and showed that this impact varied considerably. For infestation levels that did not exceed 10 galls per stem,[10] a 38% decrease in grain weight per ear was measured, and De Clercq and D'Herde[4] observed grain yield losses ranging from 12 to 15%.

Because heavy attacks of *H. marginata* can lead to severe yield losses, control methods need to be developed. Our study sought to assess the impact of this pest on winter wheat crops, given current Belgian cultural practices. We also sought to develop an efficient way of protecting cereal crops with insecticide, with application timing based on flight monitoring, during periods of heavy *H. marginata* infestation.

2 MATERIALS AND METHODS

2.1 Winter wheat trials

Two similar field trials were conducted in 2012 and 2013 in Belgium, one at Veurne (latitude 51.07° N, longitude 2.72° E, 2 m amsl) and the other at Blankenberge (latitude 51.29° N, longitude 3.14° E, 1 m amsl). These sites are in the coastal polders, an important cereal-growing region with clay-rich soils, recognised as being particularly favourable to saddle gall midge proliferation.[4,7] The trials were implemented in winter wheat (*Triticum aestivum* L.) fields (cultivar Carenius in 2012 and cultivar Henrik in 2013) that were heavily infested with *H. marginata*, the pest infestation being facilitated by the important occurrence of cereals in the cropping history.

The experimental design consisted of 68 plots of 30 m^2 (3 × 10 m) in 2012 and 64 plots of 19.5 m^2 (3 × 6.5 m) in 2013. In each year, 12 treatments were compared (including one control), based on a Latin-square-like design with 12 horizontal blocks and four vertical blocks, with each treatment appearing only once in each block. In addition, 20 (in 2012) and 16 (in 2013) untreated systematic controls were added on five (in 2012) and four (in 2013) equally spaced additional lines to improve the estimation of field heterogeneity.

The meteorological data (air temperature and precipitation) for both sites were recorded using a pluviometer and a ThermoPuce® (Waranet Solutions SAS, Auch, France) placed 1 m above ground level and checked daily.

2.2 Monitoring *H. marginata* flights

In order to determine the optimal date for insecticide application, *H. marginata* flights were monitored each year using three water traps set 40 m apart in untreated plots. These Flora® yellow traps (Signe Nature, La Chapelle d'Armentières, France) were fixed onto a cane at 0.20 m above ground level and filled with 1 L of soapy water, which was renewed twice a week. Captured insects were collected each morning, from 19 April to 22 June 2012 and from 29 April to 10 July 2013. Saddle gall midge adults were then identified using the identification key for the Cecidomyiidae developed by Skuhravá[11] and counted using a stereomicroscope.

2.3 Chemical control

The insecticide applied was lambda-cyhalothrin (100 g L^{-1}; Karate Zeon; Syngenta NV, Ghent, Belgium), a pyrethroid whose efficacy on *H. marginata* had been demonstrated in previous trials.[12,13] In order to vary the exposure period of wheat to *H. marginata*, 11 protection strategies were implemented (Table 1), including one or two insecticide application(s) spread over time, or four successive applications. The growth stages of the crop were assessed at each spraying date, using the Zadoks scale.[14]

Table 1. Description of applied treatments. Apart from the control, each treatment was sprayed with lambda-cyhalothrin 100 g L^{-1} CS at a dose of 0.05 L ha^{-1}

Treatment	Date A	Date B	Date C	Date D
Control	–	–	–	–
Treatment A	X	–	–	–
Treatment B	–	X	–	–
Treatment C	–	–	X	–
Treatment D	–	–	–	X
Treatment AB	X	X	–	–
Treatment BC	–	X	X	–
Treatment CD	–	–	X	X
Treatment AC	X	–	X	–
Treatment BD	–	X	–	X
Treatment AD	X	–	–	X
Treatment 4×	X	X	X	X

The insecticide was sprayed using a backpack sprayer fitted with a 3 m boom, at a volume of 200 L mixture ha^{-1}. The control was sprayed only with water. In both years, the first application was made a few days after the first flight peak (i.e. on 4 May 2012 and 22 May 2013). Subsequent spraying took place at intervals of about 10 days in 2012 and 14 days in 2013, so as to cover the whole flight period. In 2012, a bias was induced in the treatment D results because there was lashing rain in the hour following the spraying, rendering the insecticide treatment inefficient.

2.4 Evaluating *H. marginata* damage and yield measurement

Damage levels were assessed by randomly collecting 30 stems in each plot at the end of the larvae's feeding phase (i.e. on 10 July 2012 and 31 July 2013). The leaves and leaf sheaths were then removed from the stems, and the galls on each internode were counted.

The plots were harvested using a Haldrup experimental combine-harvester fitted with a 3 m cutter bar on 11 August 2012 and 29 August 2013. The harvest from each plot was weighed immediately in the field, and a sample (1 kg) of grain was put into a plastic bag for moisture measurement. The yield of each plot was expressed in kg grain ha^{-1} (15% humidity).

2.5 Statistical analysis

The data from each year were analysed separately using R 3.0.1. (R Development Core Team, Vienna, Austria; http://www.R-project.org). An initial series of statistical analyses were conducted to assess the effect of the insecticide treatments on two dependent variables – the number of galls per 100 stems and the yield (kg ha^{-1}) – using linear mixed models with a Gaussian distribution. The treatments were defined as fixed explanatory variables, whereas the horizontal and vertical blocks were used as crossed random effects. The number of galls per 100 stems was square root transformed in order to limit heteroscedasticity problems. The application conditions were checked using residual plots. For all models, the significance of difference among treatments was tested using likelihood ratio (LR) tests (analysis of deviance). When the likelihood ratio test was significant, all

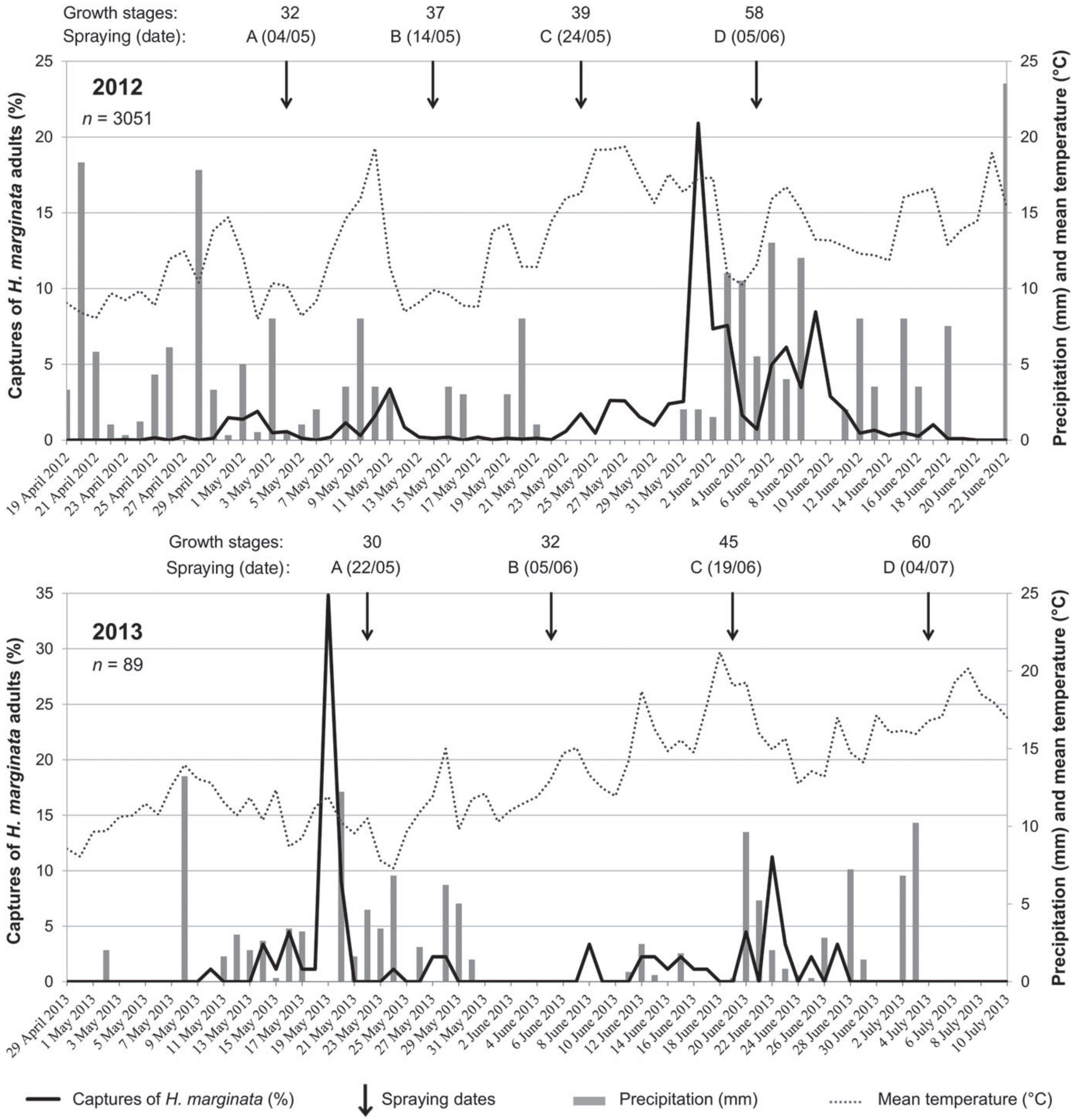

Figure 1. *H. marginata* flight patterns in trial fields in 2012 ($n = 3051$) and 2013 ($n = 9$), with meteorological data and growth stages[14] at each spraying date.

the pairwise comparisons between treatments were performed, and the *P*-values were corrected for multiple comparisons, using a generalisation of Tukey's test.[15] It is important to note that the data on damage levels and yield were not observed values but the values estimated via the statistical model, taking account of the block effects.

A second series of analyses were conducted to assess the direct relationship between the number of galls per 100 stems and the yield (kg ha^{-1}). Yield was the dependent variable and was analysed using a mixed linear model with a Gaussian distribution of residuals. The number of galls per 100 stems was used as a fixed explanatory variable, whereas the horizontal and vertical blocks were used as crossed random effects.

3 RESULTS

3.1 Monitoring *H. marginata* flights and gall distribution

The flight patterns of *H. marginata* can vary greatly from one year to the next and are weather related (Fig. 1). In 2012, the flights were very spread out and the captures were abundant: the first *H. marginata* adults were caught on 25 April and the last on 19 June ($n = 3051$). Most captures (61%) occurred between 1 and 9 June, after stem elongation, and the galls were therefore distributed only on the upper internodes, with, on average, 40% of them on internode 1 (uppermost node) and 59% on internode 2.

In 2013, the flights occurred later and were less abundant, with *H. marginata* adults being caught from 10 May to 27 June ($n = 89$). Although the galls were distributed on the four internodes, on average 80% of them were on the uppermost internode in the control plots. This suggests that the main emergences recorded on 19 and 20 May, before the beginning of stem elongation (growth stage 30), caused very little damage, with less than 1% of the galls occurring on the two lower internodes. This limited damage was probably due to the lashing rain that occurred just after the flight peak (12.2 mm on 20 May) (Fig. 1), which would have killed any adults present in the crop and removed the eggs from the leaves, as previously observed by Golightly.[6] In 2012, as in 2013, only the latest emergences appeared to induce damage. It should also be noted that the growth stages of winter wheat were put back by about 1 month in 2013 compared with 2012, owing partly to climatic conditions but mainly to delay in the sowing date.

3.2 Efficacy of insecticide treatments

In 2012, as in 2013, the damage levels showed highly significant differences among the treatments (2012: LR = 134.9, df = 11, $P < 0.0001$; 2013: LR = 88.42, df = 11, $P < 0.0001$) (Fig. 2).

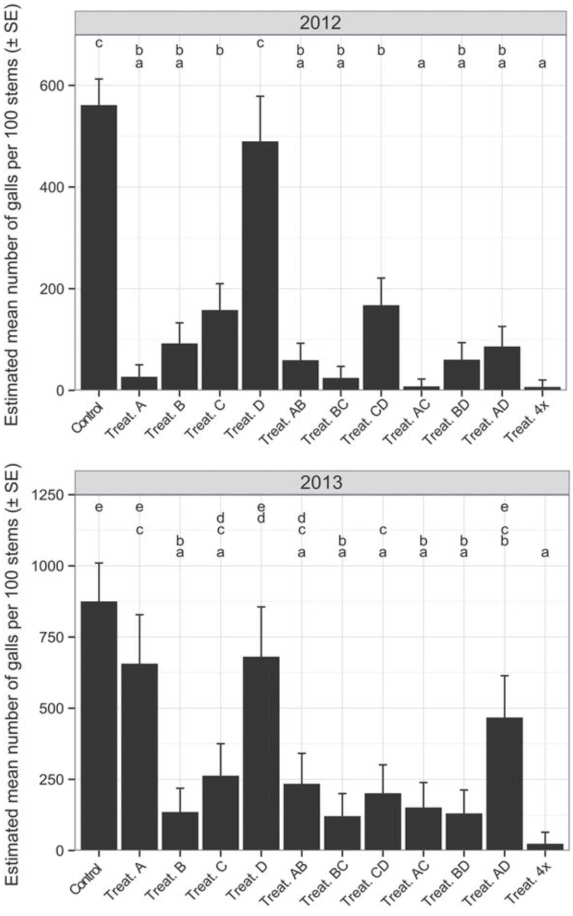

Figure 2. Estimated mean number of galls (± SE) in relation to applied treatments in 2012 and 2013. Means with at least one common letter are not significantly different based on a Tukey-like test ($\alpha = 0.05$). The treatment D results for 2012 should not be taken into account because of the lashing rain that occurred in the hour following spraying.

In 2012, most of the insecticide treatments were efficient and were significantly different from the control ($P < 0.05$), for which the estimated mean infestation reached 560 galls per 100 stems, apart from the final treatment (treatment D: 490 galls per 100 stems). Treatments based on a single application showed that, the earlier the spraying, the more it reduced gall numbers. The most efficient treatments were treatments A, BC, AC and 4×, with an estimated mean reduction in gall numbers ranging from 95 to 99%.

In the days after the first insecticide spraying (date A: 4 May 2012) there was an unexpected observation: large numbers of intoxicated larvae on the ground in treated plots. In order to assess the extent of this phenomenon, visible larvae on the ground were randomly counted on 10 May 2012 over 1 dm^2 (10 × 10 cm) of soil surface in four treated plots and in four control plots. Six separate assessments were made in each plot: three in areas of dense vegetation and three in areas of sparse foliage, and the number of larvae was expressed per m^2. On average, 2600 ± 2700 larvae m^{-2} were counted in the treated plots and only 40 ± 65 larvae m^{-2} in the control plots. This high standard deviation could be explained by the variability in soil infestation levels and/or by the limited number of observations. In the treated plots, the number of *H. marginata* larvae on the ground was much higher in areas with sparse cover (on average, 3600 ± 3500 larvae m^{-2}) than in those with dense vegetation (1500 ± 680 larvae m^{-2}).

In 2013, the mean infestation in the control plots reached 875 galls per 100 stems. Most of the treatments differed significantly from this mean, apart from treatments A, D and AD, where the gall number per 100 stems varied from 470 to 680 (Fig. 2). There were no significant differences among the other treatments, the damage levels of which ranged from 25 to 260 galls per 100 stems (i.e. an efficacy of 70–97%; $P > 0.05$).

3.3 Effect of insecticide treatments on yield

The yield analysis revealed highly significant differences among treatments and between the two years (2012: LR = 39.4, df = 11, $P < 0.0001$; 2013: LR = 79.08, df = 11, $P < 0.0001$) (Fig. 3).

In 2012, the estimated mean yield for the untreated plots was 9900 kg ha^{-1}. Although a yield increase was observed for all treatment strategies, only three of them differed significantly from the control ($P < 0.05$): treatments AB, CD and 4×, where the mean yields were 10 400, 10 415 and 10 525 kg ha^{-1} respectively.

In 2013, the estimated mean yield in the control plots was 9700 kg ha^{-1}, and the impact of the insecticide applications was greater than in 2012. Most insecticide treatments led to a significant yield increase compared with the control ($P < 0.05$), ranging from 980 to 1870 kg ha^{-1} (i.e. a yield gain of 9–19%), apart from the earliest treatment based on a single application (treatment A: 10 565 kg ha^{-1}).

In both years, insecticide applications had a similar effect on the crops: the more efficient they were in reducing gall numbers per 100 stems, the greater the yield increase compared with the control.

3.4 Relationship between yield and gall number per 100 stems

The relationship between gall number per 100 stems and yield was well described by a linear relationship (Fig. 4). In a given situation, therefore, each increase of 100 galls per 100 stems resulted in a constant yield loss. In 2012, for example, when the gall number per 100 stems rose from 0 to 100, the yield fell from 10 387 to 10 316 kg ha^{-1} (LR = 26.3, df = 1, $P < 0.0001$) (i.e. a yield loss of 71 kg ha^{-1}). In

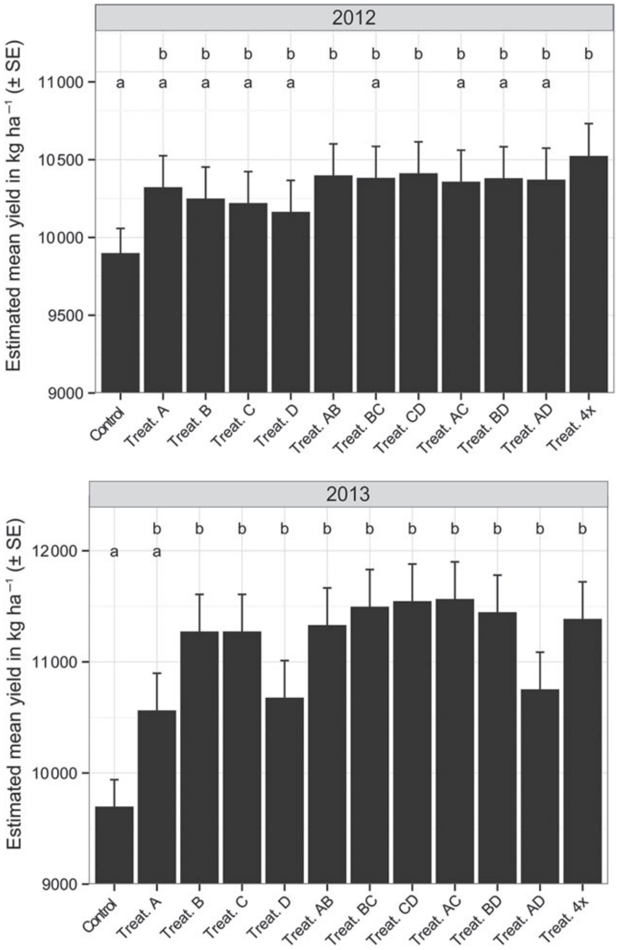

Figure 3. Estimated mean yield (± SE) in relation to applied treatments in 2012 and 2013. Means with at least one common letter are not significantly different based on a Tukey-like test ($\alpha = 0.05$).

2013, the impact of *H. marginata* larvae on yield was even greater, with the yield loss reaching 191 kg ha^{-1} for each increase of 100 galls per 100 stems (LR = 109.7, df = 1, $P < 0.0001$).

4 DISCUSSION

Monitoring adult flights enables the risk that *H. marginata* poses for a crop to be assessed and the optimal timing for insecticide applications to be determined. Capture patterns from unspecific traps, however, are not always representative of attack intensity or gall distribution on stems. Therefore, they do not allow prediction of the damage that will be inflicted on crops. In proportion to the damage levels in the control plots, 50 times fewer insects were trapped in 2013 ($n = 89$) than in 2012 ($n = 3051$), whereas the most severe damage (in the control plots) occurred in the second year of the experiment. This paradox could be explained by the major influence of climatic conditions on the success of the epigeal phase: eggs could be easily removed from leaves by wind and heavy rain. The pupae located flush with the soil and the adults could also be exposed to the destructive effect of lashing rain. In 2013, therefore, after the flight peak that occurred just before the thunderstorm of 20 May, there were no galls on the lower internodes that were available for colonisation at the time, whereas the flights in the last 10 days of June resulted in significant damage on the upper internodes, although there were far fewer individuals. The regular and abundant rainfall recorded in 2012 probably had a similar impact during the adult emergence, egg laying and egg maturation stages.

The efficacy of lambda-cyhalothrin-based treatments varied greatly, depending on spraying date and year. In 2013, only those treatments based on at least one insecticide application on dates B or C resulted in efficient protection against saddle gall midge attacks (i.e. when insecticide was applied during the damaging flight period between 5 and 30 June). Conversely, applications on dates A and D did not significantly reduce gall numbers: the first application was made during the first flight peak which resulted in no damage; the second was made 6 days after the last *H. marginata* captures, when most of the larvae were protected under the leaf sheaths. These results highlight the need to apply insecticide on the days following flight peaks if the treatment is to be effective, so that the target comprises not only the adults in the crop but also the eggs and, particularly, the young larvae crawling to their feeding site. These observations accord with findings reported in previous studies.[4,12,16]

In 2012, flights recorded between 1 and 9 June resulted in the greatest damage in the untreated plots, which was probably related to the insects pupating in the control plots just after the first spraying date. In contrast, in plots treated on date A, the larvae would have been intoxicated by lambda-cyhalothrin at the first spraying and there would not have been any flights in early June. This hypothesis is supported by the very low gall numbers observed on the upper internodes in treatment A. Because of the low foliage density at the time of this treatment, a significant portion of the spray would have reached the ground. With high soil wetting, the insecticide would have percolated through to the larvae in the first centimetre(s), just before their pupation. Like other pyrethroids, lambda-cyhalothrin is known to provoke insect excitation during the initial intoxication.[17] In our trial, this insecticide characteristically caused the larvae to emerge from the soil in the treated plots. The insecticide would have had lethal effects, preventing pupation and adult emergence, as well as sublethal effects, with the larvae that became adults being unable to breed. The effect of these insecticide treatments appeared to lessen over time, as the crop's spray interception percentage in 2012 rose from 50 to 90% (Van Beinum W and Beulke S: http://www.pfmodels.org/downloads/EMW5_11.pdf) between 4 May (treatment A, second node visible) and 5 June (treatment D, ear emergence complete) (Fig. 1).

If application timing is a key element, it is also necessary to know how many treatments should be carried out. In the case of a single flight peak, one treatment made under favourable weather conditions is usually enough to protect crops against *H. marginata*. In 2013, for example, the treatment involving four successive applications was not significantly more efficient than treatments based on a single spraying synchronised with damaging flight peaks (treatments B and C). Mölck[16] noted that significant yield losses can be avoided with a single insecticide treatment. When flights are spread over a long period, however, a single treatment is not enough to cover the entire emergence period, and several applications are therefore required.[12,13,18] Good meteorological conditions are also crucial to the success of insecticide treatment. This was the case, for example, with the last application in 2012 (treatment D) which, although synchronised with the period of most captures, turned out to be inefficient because of the heavy rains that occurred just after spraying (Fig. 1).

Insecticide treatments led to significant yield increases in 2012 as well as in 2013. In both years, these increases were probably

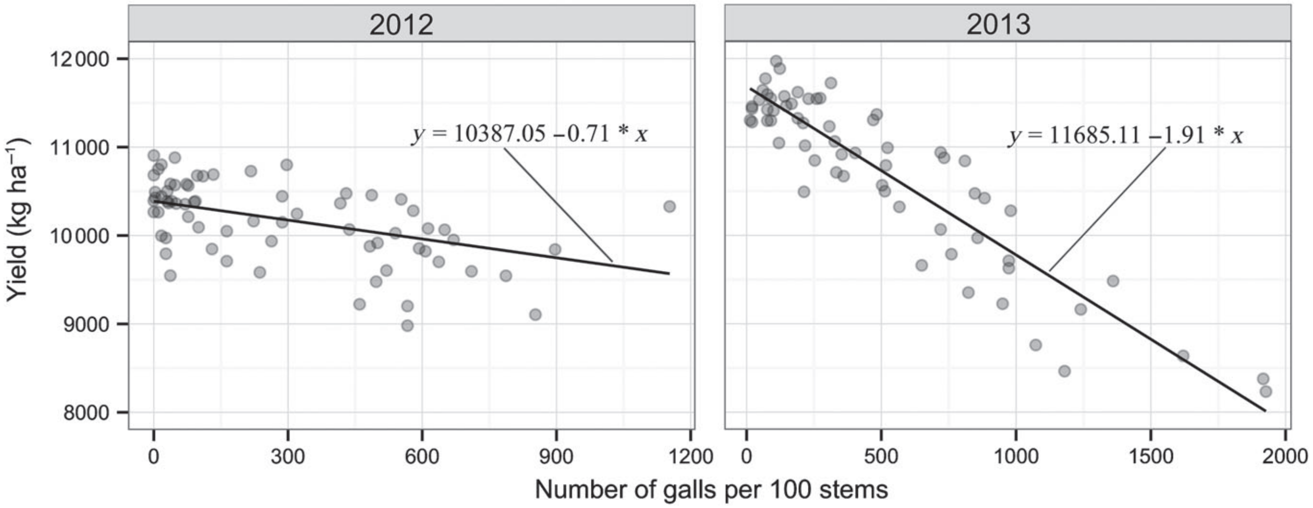

Figure 4. Number of galls per 100 stems in relation to yield in 2012 and 2013. Dots correspond to the observed values, and curves to the predicted values.

due to the effect of insecticide on *H. marginata* and not on other pests. Very low population levels of aphids, thrips and cereal leaf beetles were observed in the trials, as they were throughout Belgium in 2012 and 2013.[19,20] The orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin), was present, but flights recorded at the experimental sites were low in 2012, and in 2013 they did not coincide with the susceptible growth stages (from ear emergence to the end of flowering) of wheat (Chavalle S, unpublished).

A non-experimental correlational study was also carried out to assess the relationship between yield and gall number. Our study showed a linear relationship between these two variables: each larva that developed on stems caused the same yield loss for a given field (Fig. 4). For the same infestation level, however, the impact of attacks and galls can vary greatly from one situation to another and depends on several factors. The choice of variety is likely to play a major role, with previous studies revealing significantly different levels of varietal susceptibility.[7,21] The impact of galls on yields can also be strongly determined by the location of damage on plants, which is influenced by flight patterns and environmental conditions, as well as by cultural factors such as sowing date and crop development timing. In cereals, the earlier the growth stage at the time of *H. marginata* attacks, the more damage is likely to be caused.[4,7,22]

5 CONCLUSIONS

Attacks by *H. marginata* are usually so inconspicuous that they go unnoticed, but this pest can inflict considerable damage in the case of heavy infestations, causing significant yield losses. Pyrethroid insecticides offer an efficient way of controlling *H. marginata*, but they need to be applied in the days following a flight peak if environmental conditions are conducive to egg laying and egg development. It is essential, therefore, to carry out accurate flight monitoring in order to assess population levels and determine whether it is necessary to spray and, if so, when to spray. To this end, it would be useful to develop a specific trap for *H. marginata* and to establish the capture threshold at which this pest represents a significant risk to crops. Our experiments also highlighted the effects of insecticide applied in early spring on larvae flush with the ground, prior to their pupation.

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