Using physical barriers to prevent carrot fly (Psila rosae (Fabricius)) damage in domestic production

1   <u>Abstract</u>

2   A field experiment ~~employing a randomised block design~~ was used to assess the effectiveness of

3   different barriers in protecting garden-scale carrot production from carrot fly (*Psila rosae* (Fabricius))

4   damage. Some of the vertical barriers tested were found to provide a useful method of protecting

5   early season carrots from carrot fly in terms of the percentage of carrots free from damage but, under

6   cumulative pest pressure of several generations of carrot fly, such barriers were found to provide

7   insufficient protection. Gardeners should therefore completely cover their carrot crop to attain an

8   acceptable level of control, this was found to be especially important for carrots harvested later in the

9   season. There were positive effects of some barrier types on yield which may be due, at least in part,

10   to the protection given by the barriers to carrot seedlings.

11

14

15

16   Introduction

17   Carrot fly (*Psila rosae* (Fabricius)) is an important pest of apiaceous crops including carrots, parsnips,

18   celery and parsley both in commercial production and for the home gardener (Fox Wilson, 1945;

19   Collier & Finch 2009). Crop damage is caused by the fly larvae which feed on the developing roots

20   (Coppock, 1974). Early season damage can kill young seedlings and the tunnelling of larvae in more

21   developed roots reduces quality and affects storage (Coppock, 1974). Since 1967, when computerised

22   records began, more than 81% of all carrot pest enquiries from Royal Horticultural Society members

23   have related to carrot fly damage. In addition, many gardeners are entirely put off from growing

24   carrots due to expected damage from carrot fly (G. Barter, pers. comm.).

25

26   Female carrot flies enter carrot crops from field boundaries and lay eggs around plants either singly

27   or in small clumps of up to seven, approximately 3-6 mm under the soil (Petherbridge, Wright &

28   Davies, 1942; Ellis, Freeman, Dowker, Hardman & Kingswell, 1987). In the UK, carrot flies have two

29   generations per year with a partial third generation at some warm sites in the south (Collier & Finch,

30   2009). After the initial colonisation of carrot crops from boundaries, flies from subsequent generations

31   can emerge from within the crop. Emergence period varies from year to year and between sites

32   (Barnes, 1942) but can be predicted using a simulation model that is run with air and soil temperatures

33   (Collier, Finch & Phelps, 1992). There is some evidence that, with climate change, damage from carrot

34   fly may worsen both due to higher average temperatures during the second generation leading to a

35   longer emergence period (as demonstrated during the 2013 and 2014 seasons) and the climatic

36   conditions leading to a damaging third generation becoming more common in the UK (Jukes, Elliot,

37   Mead & Collier, 2016).

38   Control options for the home gardener for this pest are limited. Although some pesticides are licenced

39   for use in agricultureindustry against carrot fly, mainly pyrethroids applied either as seed treatments

40   or foliar sprays (Jukes *et al.*, 2016), there are no chemical treatments available to amateur gardeners

41   (Pollock, 2008). Despite concern from home gardeners, and the challenges involved in controlling

42   carrot fly, the most recent research focussing on developing controls for home gardeners was

43   published by the RHS in the 1940s (Fox Wilson, 1945). This ~~previous~~ project, ~~which~~ investigated the

44   effect of staggered sowings, harvesting date and planting site on carrot fly damage, was small in scale

45   and designed to assist with the control of carrot fly in gardens. More recent research has focussed on

46   large-scale infestations in agricultural systems (for review see Collier & Finch, 2009).

47   In the absence of effective pesticides, the main methods of control used by home gardeners are either

48   cultural or physical. Cultural controls are most often based around sowing dates. Carrots that are sown

49   late (i.e. after mid-May) avoid the first generation of this pest whilst carrots harvested before late

50   August avoid damage by the second generation (Pollock, 2008) but in order to achieve a reasonable

51   length of growing season all carrots are likely to face attack from at least one generation of the pest.

52

53   This study focusses on physical control methods. One of the most widely used and effective physical

54   method_s_ used by home gardeners is to completely cover the crop with insect-proof netting which

55   excludes the adult fly, preventing egg laying. Completely ~~C~~covering ~~completely~~plants has

56   disadvantages; the process of covering can be relatively labour intensive and expensive whilst plot

57   maintenance can be made more difficult since access for activities such as weeding and thinning is

58   restricted. Finally, by affecting the microclimate, covering can favour fungal diseases and weeds

59   (Siekman & Hommes, 2007).

60

61   An alternative to completely covering crops is to use a barrier fence. The theory behind the use of

62   fences is that adult carrot flies ~~(and the adults of other related species)~~ are relatively weak fliers which

63   tend to fly close to the ground whilst looking for host plants (Judd, Vernon & Borden, 1985). Using

64   yellow sticky traps positioned at varying heights at the edges of crops Judd *et al.* (1985) found that

65   early in the season the largest proportion of *P. rosae* was captured 10 to 20 cm above the soil or 5 to

66   10 cm above the crop. Above a height of 80 cm significantly fewer flies were caught. From this

67   evidence barriers were proposed to be able to modify flight direction and alter where and how often

68   carrot flies land (Boiteau & Vernon, 2001). Using a structure specifically as a physical barrier to stop

69   pest insects accessing plants has been established for 40 years (Weintraub, 2009). The use of barrier

70   fences, as opposed to completely covering the crops, was first reported as a novel method in the

71   scientific literature by Vernon and Mackenzie (1998) to protect swede from cabbage root flies (*Delia*

72   *radicum* (L.)) although unpublished work by Garden Organic pre-dates this (Margi Lennartsson, pers.

73   comm.). Barrier methods have been shown to be effective against carrot fly and ~~related~~ other pests

74   ~~in several studies,~~ for example Jukes, Collier & Elliott (2009) ~~who~~ found that a 1.7 m fence surrounding

75   plants decreased the number of carrot fly adults caught on yellow sticky traps ~~to 15 %~~by 85% when

76   compared to those ~~of the number caught~~ outside the barriers. Vernon and Mackenzie (1998) showed

77   that there was an inverse linear relationship between fence height and the number of cabbage flies,

78   a pest with stronger flight strength than carrot fly, that were able to enter~~ing~~ a swede plot.

79

80   This study explores barrier efficacy, testing different barrier heights and designs to find the method

81   most effective at minimising carrot fly damage, whilst being feasible for application by the home

82   gardener. Most testing of barriers against carrot fly has been done on a field-scale basis making results

83   potentially inapplicable to home gardeners. Even when plot sizes are small (for example in Siekmann

84   & Hommes, 2007) fence height is still up to 1.7 m tall, a height impractical to all but the most

85   determined home gardeners. Shorter barriers are considered more convenient for gardeners as plot

86   maintenance is easier. If shorter barriers give some protection compared to no barrier at all then

87   perhaps some gardeners would find these shorter barriers preferable. To make the study applicable

88   to home gardeners, small (1.5 m^2) plots were used and popular control methods employed by

89   gardeners were tested; 'fences' (barriers) of several different heights, together with complete plot

90   covering.

91

92

93   <u>Methods</u>

94   This field experiment ~~used a randomised block design to~~ assess<u>ed</u> the effectiveness of different barrier

95   heights and designs. The experimental plots were located at the Royal Horticultural Society's field

96   study site at Deer's Farm, Surrey<u>, UK</u> (<u>Grid ref:</u> TQ 064 592). The field work occurred during the spring,

97   summer and autumn of 2016.

98   The soils of the field site belong predominantly to the Bagshot Beds soil formation which is

99   characterised by free draining sandy loam, suitable for carrot cultivation (Fox Wilson, 1945; Jarvis *et*

100   *al.*, 1984). The field site, previously amenity grassland, was prepared in March 2015; the soil was

101   mechanically rotavated and, after analysis, was fertilised for best carrot growth <u>(according to</u>

102   <u>Department for Environment, Food & Rural Affairs Nutrient Management Guide RB209,</u>

103   <u>2010)</u>~~according to Defra RB209~~ by applying sulphate of potash at 35 g/m^2 and ammonium sulphate at

104   33 g/m^2.

105   A plot adjacent to the experimental site was sown with carrots in the season preceding this experiment

106   (May 2015) to attract carrot fly to the site, creating a source of the pest which would then overwinter

107   ~~ready to emerge~~ and infest the carrots grown for this study. Two 15 m rows of Nantes 2 Early (Lge)

108   carrots (Marshalls Seeds, UK) were sown on the 27th March 2015 with a second sowing of two rows

109   on the 26th May 2015. These source carrots were harvested on the 20th October 2015 and damage

110   levels recorded. The infestation level was low; approximately 7 % of carrots were damaged by carrot

111   fly. ~~It did, however, show that that the pest could migrate from other nearby sites despite its assumed~~

112   ~~poor dispersal ability.~~

113

114   For the main study<u>,</u> Nantes 2 Early (Lge) seeds (Marshalls Seeds, UK) were sown on the 22nd March

115   2016 (~~early~~ <u>first</u> sowing) and 2nd June 2016 (<u>second</u>~~late~~ sowing) into 40 1.5 x 1.5 m plots. Sowing was

116   timed so that ~~plants at suitable developmental stages~~<u>seedlings</u> were available for host searching

117   carrot fly in April, May and August.

118

119   The plots were arranged into eight five-plot experimental blocks, each containing one plot of the five

120   treatments: no barrier, 60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and complete

121   cover, arranged randomly within them. These blocks ran parallel to a 3 m high alder (*Alnus glutinosa*)

122   hedge and potential carrot fly source population (the bed in which source carrots had been sown in

123   2015) which ran along the north of the plots. This orientation was chosen because it is known that

124   adult carrot flies aggregate in sheltered areas near their food source, the nectar of wild flowers, and

125   it is from these areas that females migrate into the crop to lay their eggs (Ellis *et al.*, 1987). The location

126   of the hedge and source population in relation to the plots were therefore assumed to be the biggest

127   potential bias in the experiment and this was taken into account by setting out the experimental blocks

128   in parallel to these features. Each of the rows of plots were numbered, beginning with the row nearest

129   the hedge and carrot fly source. These row numbers served as a proxy for a measured distance from

130   the hedge.

131   Plots were separated by a gap of 1 m which served as access for weeding, thinning and harvesting.

132   Each plot contained a total of four rows of carrots, with two rows sown for the first~~'early'~~ sowing in

133   March and two rows being sown in the ~~'late'~~ second sowing in June. The seeds were sown at a rate of

134   approximately 100 seeds/m (150 seeds per 1.5 m row). ~~This rate was achieved by first calculating the~~

135   ~~average weight of 150 carrot seeds based on the weight of 10 batches of counted seeds. This average~~

136   ~~weight was then used to weigh out batches of approximately 150 seeds, one batch for each row. Each~~

137   ~~batch was then sprinkled at an approximately even rate over the 1.5 m row.~~

138   Immediately after the first seed sowing, barriers were erected around the plots. The barriers and plot

139   coverings were constructed using wooden stakes and insect-proof netting (polythene 16

140   threads/sq.in. (Fargro Ltd., UK)).

141   In this study barriers of 60 cm were used as the 'short' barriers as these are the minimum height

142   usually recommended (e.g. Pollock, 2008), are available for home gardeners to buy commercially and,

143   according to the findings of Judd *et al.* (1985), should intercept the majority of the flies. The tallest

144   barriers used in this study were 90 cm. These are also available commercially for home gardeners and

145   should be expected to improve protection by intercepting more flies. It should be noted that home

146   gardeners also construct their own barriers which vary in height and reported efficacy. The final type

147   of barrier tested was a 60 cm barrier with the addition of a 20 cm 'overhang' positioned at a 45° angle

148   to the top of the outside of the barrier. It is thought that an 'overhang' may improve the efficacy of

149   the barrier, based on observations of Malaise traps where flying insects encountering a barrier fly

150   upwards and become trapped in a collection bottle at the structure's apex (Vernon & Mackenzie,

151   1998). In previous experiments an overhang at a 45° angle at the top of a barrier has been found to

152   significantly improve fly catches (Bomford, Vernon, & Päts, 2000). Since space limitations prevented

153   adding the overhang to both the 60 cm and 90 cm barrier treatments, the 60 cm barrier was chosen

154   as, since this is the most commonly recommended barrier height for gardeners, it was thought

155   worthwhile to see if its performance could be improved with a simple alteration.

156   Some plots were also completely covered in insect-proof netting in order to determine the minimum

157   levels of damage that could be expected. Plots without any barrier or covering acted as a control

158   treatment.

159

160   Plots were maintained following RHS advice to mirror garden management practices so that the

161   results could be as relevant as possible to amateur gardeners. Plots were weeded when necessary,

162   approximately once every two weeks. Overhead irrigation was used ~~when the weather was dry~~as

163   necessary. After germination, carrots were thinned to a 5 cm spacing within plants. Poor emergence

164   or early carrot fly attack (the relative contribution of each cannot be ascertained from these results)

165   left gaps of more than 5 cm in some plots, especially those that were completely uncovered. Thinning

166   effort was therefore not constant between plots, but effectively resulted in a maximum seedling rate

167   of approximately 30 plants per row with plots where the majority of seeds had germinated being

168   thinned to this number and in the plots where seed emergence was poor, less thinning took place but

7

169 often fewer than 30 seedlings per row resulted. The number of seedlings per row ranged from 3 to 36

170 with the average number across all plots being 25.

171 The timing of seed sowing and damage counts was calculated to distinguish damage caused by the

172 first and second generation carrot flies. Plants from the first sowing were harvested and assessed on

173 19th-22nd July 2016 and those from the second sowing on 21st- 25th November 2016. Carrot fly larvae

174 continue feeding throughout the winter and deterioration of the roots is most rapid in October and

175 early November, meaning the damage count in November is likely to be worse than in September

176 (Petherbridge *et al*., 1942). The timing of the second damage measure was left purposefully late in the

177 season so as to view the most extreme levels of damage that could occur using the different methods

178 of protection.

179

180 The variables recorded from each plot were: distance from the hedge and carrot fly source, the total

181 number of roots and fresh harvest root weight. All roots were harvested and each root was assessed

182 individually for damage by carrot fly larvae. All roots from a plot were harvested as opposed to a

183 subset or samples since previous studies have shown that, in the case of carrot fly damage

184 assessments, the smaller the area of the experiment, the greater the number of samples that must be

185 lifted, as otherwise the level of damage is underestimated (Fox Wilson, 1945).

186 Each root was assigned to a damage category based on a visual survey approximating the percentage

187 of the surface area damaged (see Table 1) after Jukes *et al*. (2009). The damage categories were 0%,

188 <5%, 5 − 10%, 10 − 25% and 25 − 50% of the surface area affected by carrot fly. These equated to

189 damage scores of 0, 1, 2, 3, 4 and 5 respectively. A measure of 'damage severity' was calculated by

190 dividing the sum of the carrot damage scores in the plot by the total number of damaged carrots per

191 plot. The severity is therefore the average damage score seen on damaged carrots in the plot. A low

192 severity score would indicate that, of the carrots that were damaged, this damage was generally of a

193 low level.

194 Damage severity was used in tandem with the ~~Two measures were used to quantify the level of~~

195 ~~damage by carrot fly in plots protected by the different barrier methods. Firstly the~~ proportion of

196 harvested carrots that were undamaged by carrot fly (after Jukes *et al*, 2016) ~~was calculated for each~~

197 ~~plot~~to quantify the level of damage . Carrots that are completely undamaged by carrot fly may be

198 considered by gardeners to be highly preferable when compared to even those damaged to a low

199 degree. This is because any carrot fly damage will affect, not only the aesthetic appeal of a carrot, but

200 will also affect storage, meaning that they must be eaten before secondary rots set in. Roots attacked

201 by carrot fly are also more susceptible to frost damage than undamaged carrots (Petherbridge *et al*,

202 1942). ~~The second, complementary, measure used was damage severity. This is the mean damage~~

203 ~~score of all the damaged carrots in a plot. A low severity score would indicate that, of the carrots that~~

204 ~~were damaged, this damage was generally of a low level.~~

205 In this experiment a barrier treatment can be considered to have been more successful than another

206 if it has a higher proportion of undamaged carrots and a lower severity score. This would mean that

207 few carrots were damaged and, those that were, had only a low level of damage

208

209 For the ~~late~~ second sowing, in order to estimate root yield per plot, a representative sub-sample was

210 taken from each plot; either 16 roots, or a quarter of the roots retrieved, whichever was greater.

211 Where plots had had fewer than 16 roots in total, all roots were included. The wet weight of each

212 subsample was recorded (in addition to the wet weight of all the roots in the plot), roots were then

213 sliced into cross sections no more than 5 mm in width and dried in an oven at 100˚C for seven days

214 before being re-weighed to obtain dry mass for each subsample.

215 Variables analysed were: estimated crop yield (second sowing), the percentage of carrots undamaged

216 by carrot fly and ~~,~~ damage severity. ~~and estimated crop yield (late sowing).~~

217 Statistical analysis was conducted in GenStat (VSN International, 2017). with some graphs being

218 produced in RStudio (RStudio, 2016). For data meeting parametric analysis assumptions, one way

219 ANOVAs or chi-squared tests were performed and, where data were not normally distributed, they

220 were transformed appropriately; percentage of undamaged roots were transformed to logits and

221 severity transformed to logarithms. Interaction between treatment and sowing was included as an

222 effect and, where no significant interaction was found, mean values are presented over earlyfirst and

223 secondlate sowings. For each variable, interactions between treatment and sowing were tested for

224 and, if found, would have been analysed separately.

225

226

227   Results

228   There was no significant effect of distance from the hedge and carrot fly source on the percentage of

229   undamaged carrots in either the firstearly sowing (X^2=1.71, df=3, p>0.5) or the late second sowing

230   (X^2=0.65, df=3, p<0.5). There was no significant effect of distance from the hedge and carrot fly source

231   on damage severity for either the early first sowing (χ^2 = 0.55, 3 df, p > 0.05) or the late second sowing

232   ($F_{3, 36}$ = 0.805, p > 0.05).

233   The estimated crop yield (only calculated for carrots harvested from the the 2nd second harvestsowing)

234   differed significantly between the treatments ($F_{4, 28}$ = 5.01, p = 0.004) (Table 12). Plots unprotected

235   by a barrier produced the lowest estimated crop yield. Plots protected by 60 cm barriers had increased

236   production when compared to unprotected plots, whilst those protected by a 60 cm barrier with the

237   addition of an overhang produced a larger estimated crop yield, similar to that produced in plots

238   surrounded by a 90 cm barrier.

239   For percentage undamaged roots and severity, there was no significant interaction between

240   treatment and sowing (in both cases, F4,63<2.5, P>0.05) and therefore mean values are over first and

241   second sowings.

242   The percentage of undamaged roots differed significantly between treatments ($F_{4,35}$=23.5, p<0.001)

243   (Table 12). Plots protected by any of the three barrier treatments produced a higher percentage of

244   undamaged roots than those unprotected by a barrier, but none produced a comparable percentage

245   of undamaged carrots to those plots completely covered in insect-proof netting.

246   The severity (i.e. average damage score seen on damaged carrots in each plot) varied significantly with

247   treatment ($F_{4,35}$=12.1, p<0.001) (Table 12). The average level of damage seen on fly-attacked carrots

248   was similar between unprotected plots and those protected by the shortest barrier (60 cm). Plots

249   protected by the 60 cm barriers with an overhang and the taller 90 cm barriers had lower levels of

250 damage. None of the barrier methods, however, came close to the protection afforded by completely

251 covering the carrots with insect-proof netting.

252 ~~How the percentage of undamaged carrots and the damage severity was affected by treatment is~~

253 ~~summarised visually for the early sowing in Figure 1a and the late sowing in Figure 1b.~~

254

256   Discussion

257   ~~Two measures were used to quantify the level of damage by carrot fly in plots protected by the~~

258   ~~different barrier methods. Firstly the proportion of harvested carrots that were undamaged by carrot~~

259   ~~fly (after Jukes *et al*, 2016) was calculated for each plot. Carrots that are completely undamaged by~~

260   ~~carrot fly may be considered by gardeners to be highly preferable when compared to even those~~

261   ~~damaged to a low degree. This is because any carrot fly damage will affect, not only the aesthetic~~

262   ~~appeal of a carrot, but will also affect storage, meaning that they must be eaten before secondary rots~~

263   ~~set in. Roots attacked by carrot fly are also more susceptible to frost damage than undamaged carrots~~

264   ~~(Petherbridge *et al*, 1942). The second, complementary, measure used was damage severity. This is~~

265   ~~the mean damage score of all the damaged carrots in a plot. A low severity score would indicate that,~~

266   ~~of the carrots that were damaged, this damage was generally of a low level. In this experiment a~~

267   ~~barrier treatment can be considered to have been more successful than another if it has a higher~~

268   ~~proportion of undamaged carrots and a lower severity score. This would mean that few carrots were~~

269   ~~damaged and, those that were, had only a low level of damage~~

270   In both measures used to quantify damage by carrot fly, damage levels were greater in <u>carrots</u>

271   <u>harvested from</u> the second ~~harvest~~ <u>sowing</u> than ~~in the first harvest~~<u>from the first</u> (see Figures 1a and

272   1b). This is likely to be because damage to this second sowing of carrots occurred not only due to the

273   maggots laid by second generation flies that managed to overcome the barrier defences and enter the

274   plots, but also from eggs laid by flies that emerged within the barriers i.e. the offspring of those that

275   had entered the plots earlier in the season (Collier & Finch, 2009). This means that when using barriers,

276   damage from carrot fly is usually greater after the second or third generation, where one occurs

277   (Collier & Finch, 2009). This underlines the importance for gardeners to practice crop rotation when

278   using barriers or covers.

279   The proportion of undamaged carrots harvested from uncovered plots in <u>roots from</u> the first

280   <u>sowing</u>~~harvest~~ varied from around 0.6 to 1.0 (Figure 1a) suggesting that, in some cases, gardeners

281 might be able to achieve an acceptable harvest without protecting crops but, with a mean undamaged

282 proportion of 0.81 roots and a minimum of 0.6, this is not always the case and gardeners must be

283 prepared to accept the risk of losing almost half a carrot crop if they do nothing to protect it from

284 carrot fly. The level of damage seen in a particular plot is also likely to depend on the season's weather

285 conditions, proximity of the plot to other carrot growing sites and occurrence of alternative host plants

286 and the resulting size of the local carrot fly population. It should also be noted that this experiment

287 took place on plots where no carrots had been grown previously and not close to any other carrot

288 crops. It is therefore likely that the damage levels seen here will underestimate those likely in gardens

289 or allotments where carrots are grown regularly.

290 It has been shown in previous studies of carrot fly biology that non-crop habitats such as hedgerows

291 around carrot fields can provide shelter for, and allow aggregation of, carrot fly resulting in extensive

292 damage to adjacent carrots (Baker, Ketteringham, Bray & White, 1942; Barnes, 1942; Petherbridge &

293 Wright, 1943; Wainhouse & Coaker, 1981). Based on this previous research it was expected that in

294 this study the distance of the carrot plots from the adjacent hedge would affect the amount of carrot

295 fly damage. This was not the case, however, and there was no significant relationship between

296 distance from the hedge and either the percentage of undamaged carrots or the severity of damaged

297 of affected carrots although, had there been such a relationship, it would have been accounted for

298 between treatments by the experimental blocking. The most likely explanation of this unexpected

299 result may relate to the relatively small spatial scale of the study. Most previous studies, even those

300 considered 'small-scale', have examined the effects of carrot fly over areas much larger than the

301 current study. Fox Wilson (1945) for example, noted a higher proportion of unsaleable roots in rows

302 near to hedges when compared to those further away but the beds extended 28 m from the hedge.

303 Wright & Ashby (1946) noted a similar 'headland effect' between the headlands and an area

304 approximately 27 m from the hedge, which was defined as 'midfield'. The experimental area in this

305 study only extended approximately 15 m away from the hedge and so it is perhaps not surprising that,

306 in this case, the distance from the hedge did not produce a significant effect on the levels of carrot fly

14

307   damage. This experiment was most likely simply too small to see these differences but, if this is the

308   case, then the majority of UK gardens are also too small. The average garden size in Great Britain is 14

309   m² (Horticultural Trade Association, 2018). In garden settings therefore, there is unlikely to be enough

310   space to avoid the effects of a boundary fence or hedge on a carrot plot. Gardeners should be

311   reassured that their placement of carrot plots with respect to boundary fences should not, in ordinary

312   circumstances, make a difference to the damage levels they experience. This also demonstrates the

313   value of matching the scale of a study to that of the relevant system as, in this case, conclusions

314   reached from large scale studies of commercial production may be unhelpful to domestic production.

315   The likely reasons behind the yield differences between treatments are probably a combination of

316   poor seedling emergence and/ or early carrot fly attack leading to a difference in carrot yield (as

317   measured by the dry mass of harvested carrots from the ~~late~~ second sowing). Yield was increased by

318   covering the carrots and by some of the barrier treatments when compared to plots with no barrier

319   (Table 1~~2~~).

320   There are two likely explanations for this effect of barriers. Firstly, ~~A second factor that may have~~

321   ~~contributed to the comparatively greater yield harvested from the plots that were covered, had a 90~~

322   ~~cm barrier or the 60 cm barrier with an overhang, as compared to the uncovered crops is~~ early attack

323   by carrot fly. When carrot flies lay eggs in clumps around seedlings the resulting maggots can destroy

324   or seriously damage the plant's tap root leading to the death of many plants (Ellis *et al.*, 1987).

325   Uncovered plots which had less protection from carrot fly may have lost more roots early in the season

326   leading to the resulting lower numbers of carrots harvested and contributing to the lower yield in

327   these plots.

328

329

330   ~~Firstly barriers~~Secondly barriers can influence the microclimate around the crop, reducing wind speed

331   and evapotranspiration and therefore water stress, as well as altering the air and soil temperature

332   (Skidmore, Jacobs, & Hagen, 1972). In the case of winter wheat (*Triticum aestivum* L.) for example,

333   plants sheltered by a slat-fence wind barrier grew taller, had larger leaves, and suffered less from

334   water-stress when compared with those in an open field (Skidmore, Hagen, & Naylor, 1974). Carrot

335   yields are known to be negatively correlated with increasing water stress (Reid & Gillespie, 2017)

336   especially when this water stress occurs at the seedling emergence stage (Schmidhalter & Oertli,

337   1991).

338   ~~A second factor that may have contributed to the comparatively greater yield harvested from the plots~~

339   ~~that were covered, had a 90 cm barrier or the 60 cm barrier with an overhang, as compared to the~~

340   ~~uncovered crops is early attack by carrot fly. When carrot flies lay eggs in clumps around seedlings the~~

341   ~~resulting maggots can destroy or seriously damage the plant's tap root leading to the death of many~~

342   ~~plants (Ellis *et al.*, 1987). Uncovered plots which had less protection from carrot fly may have lost more~~

343   ~~roots early in the season leading to the resulting lower numbers of carrots harvested and contributing~~

344   ~~to the lower yield in these plots.~~

345   It is difficult from these data to ascertain the relative contribution of the effects of barrier shelter and

346   carrot fly attack on the differing carrot yields from the plots. However, the plots were well irrigated

347   when the weather was dry and the hedge running along the north of the plots is likely to have given

348   some shelter against the prevailing south-west winds. Moreover, the patterns of yield and the

349   numbers of harvested carrots follow roughly the same pattern as damage levels. Finally, the yield from

350   plots protected by a 60 cm barrier with an overhang was greater than that from those plots with a 60

351   cm barrier alone and the overhang is unlikely to have caused much of an increase in shelter but is

352   known to provide addition protection against the fly (Bomford et al., 2000) it therefore seems likely

353   that early season carrot fly attack may have been the main contributing factor. Regardless of the

354   reason however, improved yield would be of interest to carrot growers and so this information could

355 be used to make more informed decisions regarding barrier choice and whether ~~or not~~ to completely

356 cover the plots.

357 In conclusion the best option for reducing damage levels, both in terms of the percentage of carrots

358 damaged and the damage levels those carrots are subject to, is to completely cover plots with insect-

359 proof netting. This is of greater importance for carrots that will be harvested later in the season (or

360 potentially in areas where the risk of infestation is higher than that encountered in our study). It should

361 be noted that garden crop rotation practices must still be employed given that even completely

362 covering the crops did not provide total protection, allowing carrot fly of successive generations to

363 emerge within the covering if crops are not rotated.

364 Our study was conducted on one site and over one field season and so some caution must be adopted

365 in using the results to generalise to all garden sites. From the results however we recommend that,

366 ~~I~~if carrot growers are willing to accept some level of carrot fly attack, are planning to harvest their

367 carrots early and/or live in an area where this pest has not previously been a problem then they could

368 choose to install barriers, with the 90 cm and 60 cm with an overhang.~~,~~ These barriers provid~~eing~~ some

369 protection when compared to no barriers at all, whilst also being easier to install and garden within

370 when compared to completely covered plots. The percentage of carrots damaged and damage

371 severity levels encountered within the plots protected by the 60 cm barrier was significantly higher

372 than for the completely covered treatment; the levels of damage these carrots received was not

373 significantly different to installing no barrier, so may not be worth the effort for gardeners.

374 Given the prevalence of information recommending 60 cm barriers as offering sufficient protection,

375 efforts now need to be made to update advice in the light of these results and to recommend to home

376 gardeners a combination of crop rotation with completely covering carrot crops rather than the

377 currently recommended 60 cm barrier fences.

378

379   Conflict of interest statement

380   The authors have no conflicts of interest to disclose.

381

382   Author contribution

383   • Author 1, author 5 and author 6 conceived research.

384   • Author 1, author 2 and author 3 conducted experiments.

385   • Author 1, author 2 and author 4 analysed data and conducted statistical analyses.

386   • Author 2 produced the graphical figures

387   • Author 1 wrote the manuscript.

388   • Author 6 secured funding.

389   • All authors read and approved the manuscript.

390   Data availability statement

391   Authors can confirm that all relevant data are included in its supplementary information files

392

393   References

394   Baker, F. T., Ketteringham, I. E., Bray, S. P. V. & White, J.H. (1942) Observations on the biology of the

395   carrot fly (*Psila rosae* Fab.): Assembling and oviposition. *Annals of Applied Biology*, **29**: 115–125.

396   DOI: 10.1111/j.1744-7348.1942.tb07577.x

397   Barnes, H.F. (1942) Studies of fluctuations in insect populations IX. The carrot fly (*Psila rosae*) in 1936-

398   41. *Journal of Animal Ecology*, **11**: 69–81.

399   Boiteau, G. & Vernon, R.S. (2001) Physical barriers for the control of insect pests. In: Physical control

400   methods in plant protection, (ed.) Vincent, C., Panneton, B., Fleurat-Lessard, F., *Springer*. 224-

401   247.

402   Bomford, M.K., Vernon, R.S. & Päts, P. (2000) Importance of collection overhangs on the efficacy of

403   exclusion fences for managing cabbage flies (Diptera: Anthomyiidae). *Environmental*

404   *Entomology*, **29**: 795–799. DOI: 10.1603/0046-225X-29.4.795

405   Collier, R.H., Finch, S. & Phelps K. (1992) The feasibility of using models to forecast carrot fly attacks in

406   commercial carrot crops. Integrated Control in Field Vegetable Crops. IOBC/WPRS Bulletin XV/4,

407   69-76.

408   Collier, R. & Finch, S. (2009) A review of research to address carrot fly (*Psila rosae*) control in the UK.

409   *EPPO Bulletin*, **39**: 121–127. DOI: 10.1111/j.1365-2338.2009.02276.x

410   Coppock, L.J. (1974) Notes on the biology of carrot fly in eastern England. *Plant Pathology*, **23**: 93–

411   100. DOI: 10.1111/j.1365-3059.1974.tb02915.x

412   ~~Dinno, A. (2015) Nonparametric pairwise multiple comparisons in independent groups using Dunn's~~

413   ~~test. *Stata Journal*, **15**: 292-300. DOI: 10.1177/1536867X1501500117~~

414   Department of Environment, Food & Rural Affairs Nutrient Management Guide (RB209) (2010) Now

415   AHDB https://ahdb.org.uk/knowledge-library/rb209-section-6-vegetables-and-bulbs

416   Ellis, P.R., Freeman, G.H., Dowker, B.D., Hardman, J.A. & Kingswell, G. (1987) The influence of plant

417   density and position in field trials designed to evaluate the resistance of carrots to carrot fly (*Psila*

418   *rosae*) attack. *Annals of Applied Biology*, **111**: 21–31. DOI: 10.1111/j.1744-7348.1987.tb01429.x

419   Fox Wilson, G. (1945) Investigations on the control of carrot fly (*Psila rosae* F.) in gardens. *Annals of*

420   *Applied Biology*, **32**: 265–276. DOI: 10.1111/j.1744-7348.1927.tb07017.x

421   Horticultural Trade Association (2018) Garden industry statistics Available online:

422   https://hta.org.uk/learn-develop/market-information/garden-industry-statistics.html Last

423   accessed: 2nd February 2018.

424   Jarvis, M.G., Allen, R.H., Fordham, S.J., Hazelden, J., Moffat, A.J. & Sturdy, R.G. (1984) *Soils and their*

425   *use in South East England: Soil Survey of England and Wales* first edit., Harpenden: Lawes

426   Agricultural Trust.

427   Judd, G.J.R., Vernon, R.S. & Borden J.H. (1985) Monitoring programme for *Psila rosae* (F.) (Diptera:

428   Psilidae) in Southwestern British Columbia. *Journal of Economic Entomology*. **78**: 471-476. DOI:

429   10.1093/jee/78.2.471

430   Jukes, A., Collier, R.H. & Elliott, M. (2009) Integrated control of carrot pests. *AHDB Project FV 312 Final*

431   *Report.*

432   Jukes, A., Elliot, M., Mead, A. & Collier, R. (2016) Carrots: Optimising control of willow- carrot aphid

433   and carrot fly. *AHDB Project FV 445 Final Report.*

434   Petherbridge, F.R., Wright, D.W., & Davis, P.G. (1942) Investigations on the biology and control of the

435   carrot fly (*Psila rosae* F.). *Annals of Applied Biology*. **29**: 380-392. DOI: 10.1111/j.1744-

436   7348.1942.tb06142.x

437   Pollock, M. (2008) Vegetable & fruit gardening: The definitive guide to successful growing. 2nd edition.

438   Dorling Kingsley Limited, London.

439   Reid, J.B. & Gillespie, R.N. (2017) Yield and quality responses of carrots (*Daucus carota* L.) to water

440   deficits. *New Zealand Journal of Crop and Horticultural Science*, **45**: 299–312. DOI:

441   10.1080/01140671.2017.1343739

442   Schmidhalter, U. & Oertli, J.J. (1991) Germination and seedling growth of carrots under salinity and

443   moisture stress. *Plant and Soil*, **132**: 243–251. DOI: 10.1007/BF00010405

444   Siekmann, G. & Hommes, M. (2007) Exclusion fences against cabbage root fly and carrot fly. Integrated

445   Protection of Field Vegetables. IOBC/wprs Bulletin. **30**: 107-112.

446   Skidmore, E.L., Jacobs, H.S. & Hagen, L.J. (1972) Microclimate modification by slat-fence windbreaks.

447   *Agronomy Journey*, **64**: 160–162. DOI:10.2134/agronj1972.00021962006400020010x

448   Skidmore, E. L., Hagen, L. J., Naylor, D. G. & Teare, I.D.T. (1974) Winter wheat response to barrier-

449   induced   microclimate.   *Agronomy   Journal*,   **66**:   501–505.   DOI:

450   10.2134/agronj1974.00021962006600040008x

451   Vernon R.S. & Mackenzie, J.R. (1998) The effect of exclusion fences on the colonization of rutabagas

452   by cabbage flies (Diptera: Anthomyiidae) The Canadian Entomologist **130**: 153-162.

453   DOI: 10.4039/Ent130153-2

454   VSN International (2017) Genstat for Windows 19th Edition. VSN International, Hemel Hempstead,

455   UK. Web page: Genstat.co.uk

456   Wainhouse, D. & Coaker, T.H. (1981) The distribution of carrot fly (*Psila rosae*) in relation to the flora

457   of field boundaries. In Pests, Pathogens and Vegetation, Thresh, J. M. (Ed.), Pitman Advanced

458   Publishing Program, Boston, 263-272.

459   Weintraub, P.G. (2009) Physical Control: An Important Tool in Pest Management Programs. In

460   Biorational Control of Arthropod Pests Application and Resistance Management. Ishaaya, I &

461   Rami Horowitz, A. (Eds.) Springer, 317 – 324.

462   Wright, D.W. & Ashby, D.G. (1946) Bionomics of the carrot fly (*Psila rosae* F.) I. The infestation and

463   sampling of carrot crops. *Annals of Applied Biology*, **33**: 69–77. DOI: 10.1111/j.1744-

464   7348.1946.tb06277.x

465

466   <u>Table and figure legends</u>

467

468   ~~**Table 1.** Carrot fly damage scores with their numeric value after Jukes *et al.* (2009).~~

469

470   **Table <u>1</u>~~2~~.** Estimated plot dry mass (i.e. crop yield), percentage of undamaged roots per plot and

471   Severity (i.e. average damage score seen on damaged carrots in each plot). <u>For percentage</u>

472   <u>undamaged roots and severity, there was no significant interaction between treatment and sowing</u>

473   <u>(in both cases, F4,63<2.5, P>0.05)</u> ~~Interaction between treatment and sowing included as an effect~~

474   ~~but no significant interaction was found~~ and therefore mean values are over <u>first</u>~~early~~ and ~~late~~ <u>second</u>

475   sowings. *F* and *P* values apply to treatment effects.

476

477   ~~**Figure 1a.** Cumulative stacked bar charts of the percentage of carrot roots assigned to each damage severity~~

478   ~~level (bright orange = damage level 0, through to black = damage level 5) for each of the treatments (no barrier,~~

479   ~~60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and covered) for the early sowing. Error bars~~

480   ~~plotted using the standard error.~~

481

482   ~~**Figure 1b.** Cumulative stacked bar charts of the percentage of carrot roots assigned to each damage severity~~

483   ~~level (bright orange = damage level 0, through to black = damage level 5) for each of the treatments (no barrier,~~

484   ~~60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and covered) for the late sowing. Error bars plotted~~

485   ~~using the standard error.~~

486

Treatment (Transformation)		Estimated plot dry mass (g) (i.e. crop yield) (untransformed)	Percentage undamaged roots		Severity	
			(transformed to logits)	Back-transformed (%)	(transformed to logarithms)	(back-transformed)
No barrier		211	-2.88	5.3	0.548	2.5
60 cm		335	0.24	56	0.555	2.6
60 cm + overhang		467	1.46	81	0.441	1.8
90 cm		479	2.39	92	0.398	1.5
Covered		487	5.23	99	0.201	0.6
SED		73.5	0.866		0.059	
df		28	63		63	
F from ANOVA		5.01	23.5		12.1	
P from ANOVA		0.004	<0.001		<0.001	