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

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Abstract

A field experiment ~~employing a randomised block design~~ was used to assess the effectiveness of different barriers in protecting garden-scale carrot production from carrot fly (*Psila rosae* (Fabricius)) damage. Some of the vertical barriers tested were found to provide a useful method of protecting early season carrots from carrot fly in terms of the percentage of carrots free from damage but, under cumulative pest pressure of several generations of carrot fly, such barriers were found to provide insufficient protection. Gardeners should therefore completely cover their carrot crop to attain an acceptable level of control, this was found to be especially important for carrots harvested later in the season. There were positive effects of some barrier types on yield which may be due, at least in part, to the protection given by the barriers to carrot seedlings.

Keywords: barrier protection, physical control methods, damage levels, home gardeners; insect-proof netting; carrot yield

Introduction

Carrot fly (*Psila rosae* (Fabricius)) is an important pest of apiaceous crops including carrots, parsnips, celery and parsley both in commercial production and for the home gardener (Fox Wilson, 1945; Collier & Finch 2009). Crop damage is caused by the fly larvae which feed on the developing roots (Coppock, 1974). Early season damage can kill young seedlings and the tunnelling of larvae in more developed roots reduces quality and affects storage (Coppock, 1974). Since 1967~~, when computerised records began~~, more than 81% of all carrot pest enquiries from Royal Horticultural Society members have related to carrot fly damage. In addition, many gardeners are entirely put off from growing carrots due to expected damage from carrot fly (G. Barter, pers. comm.).

Female carrot flies enter carrot crops from field boundaries and lay eggs around plants either singly or in small clumps of up to seven, approximately 3-6 mm under the soil (Petherbridge, Wright & Davies, 1942; Ellis, Freeman, Dowker, Hardman & Kingswell, 1987). In the UK, carrot flies have two generations per year with a partial third generation at some warm sites in the south (Collier & Finch, 2009). After the initial colonisation of carrot crops from boundaries, flies from subsequent generations can emerge from within the crop. Emergence period varies from year to year and between sites (Barnes, 1942) but can be predicted using a simulation model that is run with air and soil temperatures (Collier, Finch & Phelps, 1992). There is some evidence that, with climate change, damage from carrot fly may worsen both due to higher average temperatures during the second generation leading to a longer emergence period (as demonstrated during the 2013 and 2014 seasons) and the climatic conditions leading to a damaging third generation becoming more common in the UK (Jukes, Elliot, Mead & Collier, 2016).

Control options for the home gardener for this pest are limited. Although some pesticides are licenced for use in agriculture~~industry~~ against carrot fly, mainly pyrethroids applied either as seed treatments or foliar sprays (Jukes *et al.*, 2016), there are no chemical treatments available to amateur gardeners

(Pollock, 2008). Despite concern from home gardeners, and the challenges involved in controlling carrot fly, the most recent research focussing on developing controls for home gardeners was published by the RHS in the 1940s (Fox Wilson, 1945). This ~~previous~~ project, ~~which~~ investigated the effect of staggered sowings, harvesting date and planting site on carrot fly damage, was small in scale and designed to assist with the control of carrot fly in gardens. More recent research has focussed on large-scale infestations in agricultural systems (for review see Collier & Finch, 2009).

In the absence of effective pesticides, the main methods of control used by home gardeners are either cultural or physical. Cultural controls are most often based around sowing dates. Carrots that are sown late (i.e. after mid-May) avoid the first generation of this pest whilst carrots harvested before late August avoid damage by the second generation (Pollock, 2008) but in order to achieve a reasonable length of growing season all carrots are likely to face attack from at least one generation of the pest.

This study focusses on physical control methods. One of the most widely used and effective physical methods used by home gardeners is to completely cover the crop with insect-proof netting which excludes the adult fly, preventing egg laying. Completely ~~C~~covering ~~completely~~plants has disadvantages; the process of covering can be relatively labour intensive and expensive whilst plot maintenance can be made more difficult since access for activities such as weeding and thinning is restricted. Finally, by affecting the microclimate, covering can favour fungal diseases and weeds (Siekman & Hommes, 2007).

An alternative to completely covering crops is to use a barrier fence. The theory behind the use of fences is that adult carrot flies ~~(and the adults of other related species)~~ are relatively weak fliers which tend to fly close to the ground whilst looking for host plants (Judd, Vernon & Borden, 1985). Using yellow sticky traps positioned at varying heights at the edges of crops Judd *et al.* (1985) found that early in the season the largest proportion of *P. rosae* was captured 10 to 20 cm above the soil or 5 to 10 cm above the crop. Above a height of 80 cm significantly fewer flies were caught. From this evidence barriers were proposed to be able to modify flight direction and alter where and how often carrot flies land (Boiteau & Vernon, 2001). Using a structure specifically as a physical barrier to stop pest insects accessing plants has been established for 40 years (Weintraub, 2009). The use of barrier fences, as opposed to completely covering the crops, was first reported as a novel method in the scientific literature by Vernon and Mackenzie (1998) to protect swede from cabbage root flies (*Delia radicum* (L.)) although unpublished work by Garden Organic pre-dates this (Margi Lennartsson, pers. comm.). Barrier methods have been shown to be effective against carrot fly and ~~related~~ other pests ~~in several studies,~~ for example Jukes, Collier & Elliott (2009) ~~who~~ found that a 1.7 m fence surrounding plants decreased the number of carrot fly adults caught on yellow sticky traps ~~to 15 %~~by 85% when compared to those ~~of the number caught~~ outside the barriers. Vernon and Mackenzie (1998) showed that there was an inverse linear relationship between fence height and the number of cabbage flies, a pest with stronger flight strength than carrot fly, that were able to enter~~ing~~ a swede plot.

This study explores barrier efficacy, testing different barrier heights and designs to find the method most effective at minimising carrot fly damage, whilst being feasible for application by the home gardener. Most testing of barriers against carrot fly has been done on a field-scale basis making results potentially inapplicable to home gardeners. Even when plot sizes are small (for example in Siekmann & Hommes, 2007) fence height is still up to 1.7 m tall, a height impractical to all but the most determined home gardeners. Shorter barriers are considered more convenient for gardeners as plot maintenance is easier. If shorter barriers give some protection compared to no barrier at all then perhaps some gardeners would find these shorter barriers preferable. To make the study applicable to home gardeners, small (1.5 m^2) plots were used and popular control methods employed by gardeners were tested; ‘fences’ (barriers) of several different heights, together with complete plot covering.

Methods

This field experiment ~~used a randomised block design to~~ assessed the effectiveness of different barrier heights and designs. The experimental plots were located at the Royal Horticultural Society's field study site at Deer's Farm, Surrey, UK (Grid ref: TQ 064 592). The field work occurred during the spring, summer and autumn of 2016.

The soils of the field site belong predominantly to the Bagshot Beds soil formation which is characterised by free draining sandy loam, suitable for carrot cultivation (Fox Wilson, 1945; Jarvis *et al.*, 1984). The field site, previously amenity grassland, was prepared in March 2015; the soil was mechanically rotavated and, after analysis, was fertilised for best carrot growth (according to Department for Environment, Food & Rural Affairs Nutrient Management Guide RB209, 2010)~~according to Defra RB209~~ by applying sulphate of potash at 35 g/m^2 and ammonium sulphate at 33 g/m^2.

A plot adjacent to the experimental site was sown with carrots in the season preceding this experiment (May 2015) to attract carrot fly to the site, creating a source of the pest which would then overwinter ~~ready to emerge~~ and infest the carrots grown for this study. Two 15 m rows of Nantes 2 Early (Lge) carrots (Marshalls Seeds, UK) were sown on the 27th March 2015 with a second sowing of two rows on the 26th May 2015. These source carrots were harvested on the 20th October 2015 and damage levels recorded. The infestation level was low; approximately 7 % of carrots were damaged by carrot fly. ~~It did, however, show that that the pest could migrate from other nearby sites despite its assumed poor dispersal ability.~~

For the main study, Nantes 2 Early (Lge) seeds (Marshalls Seeds, UK) were sown on the 22nd March 2016 (~~early~~ first sowing) and 2nd June 2016 (second~~late~~ sowing) into 40 1.5 x 1.5 m plots. Sowing was timed so that ~~plants at suitable developmental stages~~seedlings were available for host searching carrot fly in April, May and August.

The plots were arranged into eight five-plot experimental blocks, each containing one plot of the five treatments: no barrier, 60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and complete cover, arranged randomly within them. These blocks ran parallel to a 3 m high alder (*Alnus glutinosa*) hedge and potential carrot fly source population (the bed in which source carrots had been sown in 2015) which ran along the north of the plots. This orientation was chosen because it is known that adult carrot flies aggregate in sheltered areas near their food source, the nectar of wild flowers, and it is from these areas that females migrate into the crop to lay their eggs (Ellis *et al*., 1987). The location of the hedge and source population in relation to the plots were therefore assumed to be the biggest potential bias in the experiment and this was taken into account by setting out the experimental blocks in parallel to these features. Each of the rows of plots were numbered, beginning with the row nearest the hedge and carrot fly source. These row numbers served as a proxy for a measured distance from the hedge.

Plots were separated by a gap of 1 m which served as access for weeding, thinning and harvesting. Each plot contained a total of four rows of carrots, with two rows sown for the first~~'early'~~ sowing in March and two rows being sown in the ~~'late'~~ second sowing in June. The seeds were sown at a rate of approximately 100 seeds/m (150 seeds per 1.5 m row). ~~This rate was achieved by first calculating the average weight of 150 carrot seeds based on the weight of 10 batches of counted seeds. This average weight was then used to weigh out batches of approximately 150 seeds, one batch for each row. Each batch was then sprinkled at an approximately even rate over the 1.5 m row.~~

Immediately after the first seed sowing, barriers were erected around the plots. The barriers and plot coverings were constructed using wooden stakes and insect-proof netting (polythene 16 threads/sq.in. (Fargro Ltd., UK)).

In this study barriers of 60 cm were used as the 'short' barriers as these are the minimum height usually recommended (e.g. Pollock, 2008), are available for home gardeners to buy commercially and, according to the findings of Judd *et al.* (1985), should intercept the majority of the flies. The tallest barriers used in this study were 90 cm. These are also available commercially for home gardeners and should be expected to improve protection by intercepting more flies. It should be noted that home gardeners also construct their own barriers which vary in height and reported efficacy. The final type of barrier tested was a 60 cm barrier with the addition of a 20 cm 'overhang' positioned at a 45^{o} angle to the top of the outside of the barrier. It is thought that an 'overhang' may improve the efficacy of the barrier, based on observations of Malaise traps where flying insects encountering a barrier fly upwards and become trapped in a collection bottle at the structure's apex (Vernon & Mackenzie, 1998). In previous experiments an overhang at a 45° angle at the top of a barrier has been found to significantly improve fly catches (Bomford, Vernon, & Päts, 2000). Since space limitations prevented adding the overhang to both the 60 cm and 90 cm barrier treatments, the 60 cm barrier was chosen as, since this is the most commonly recommended barrier height for gardeners, it was thought worthwhile to see if its performance could be improved with a simple alteration. Some plots were also completely covered in insect-proof netting in order to determine the minimum levels of damage that could be expected. Plots without any barrier or covering acted as a control treatment.

Plots were maintained following RHS advice to mirror garden management practices so that the results could be as relevant as possible to amateur gardeners. Plots were weeded when necessary, approximately once every two weeks. Overhead irrigation was used ~~when the weather was dry~~as necessary. After germination, carrots were thinned to a 5 cm spacing within plants. Poor emergence or early carrot fly attack (the relative contribution of each cannot be ascertained from these results) left gaps of more than 5 cm in some plots, especially those that were completely uncovered. Thinning effort was therefore not constant between plots, but effectively resulted in a maximum seedling rate of approximately 30 plants per row with plots where the majority of seeds had germinated being thinned to this number and in the plots where seed emergence was poor, less thinning took place but often fewer than 30 seedlings per row resulted. The number of seedlings per row ranged from 3 to 36 with the average number across all plots being 25~~.~~

The timing of seed sowing and damage counts was calculated to distinguish damage caused by the first and second generation carrot flies. Plants from the first sowing were harvested and assessed on 19th-22nd July 2016 and those from the second sowing on 21st- 25th November 2016. Carrot fly larvae continue feeding throughout the winter and deterioration of the roots is most rapid in October and early November, meaning the damage count in November is likely to be worse than in September (Petherbridge *et al*., 1942). The timing of the second damage measure was left purposefully late in the season so as to view the most extreme levels of damage that could occur using the different methods of protection.

The variables recorded from each plot were: distance from the hedge and carrot fly source, the total number of roots and fresh harvest root weight. All roots were harvested and each root was assessed individually for damage by carrot fly larvae. All roots from a plot were harvested as opposed to a subset or samples since previous studies have shown that, in the case of carrot fly damage assessments, the smaller the area of the experiment, the greater the number of samples that must be lifted, as otherwise the level of damage is underestimated (Fox Wilson, 1945).

~~-~~Each root was assigned to a damage category based on a visual survey approximating the percentage of the surface area damaged ~~(see Table 1)~~ after Jukes *et al*. (2009). The damage categories were 0%, <5%, 5 – 10%, 10 – 25% and 25 – 50% of the surface area affected by carrot fly. These equated to damage scores of 0, 1, 2, 3, 4 and 5 respectively. A measure of 'damage severity' was calculated by dividing the sum of the carrot damage scores in the plot by the total number of damaged carrots per plot. The severity is therefore the average damage score seen on damaged carrots in the plot. A low severity score would indicate that, of the carrots that were damaged, this damage was generally of a low level.

Damage severity was used in tandem with the Two measures were used to quantify the level of damage by carrot fly in plots protected by the different barrier methods. Firstly the proportion of harvested carrots that were undamaged by carrot fly (after Jukes *et al*, 2016) was calculated for each plotto quantify the level of damage . Carrots that are completely undamaged by carrot fly may be considered by gardeners to be highly preferable when compared to even those damaged to a low degree. This is because any carrot fly damage will affect, not only the aesthetic appeal of a carrot, but will also affect storage, meaning that they must be eaten before secondary rots set in. Roots attacked by carrot fly are also more susceptible to frost damage than undamaged carrots (Petherbridge *et al*, 1942). The second, complementary, measure used was damage severity. This is the mean damage score of all the damaged carrots in a plot. A low severity score would indicate that, of the carrots that were damaged, this damage was generally of a low level.

-In this experiment a barrier treatment can be considered to have been more successful than another if it has a higher proportion of undamaged carrots and a lower severity score. This would mean that few carrots were damaged and, those that were, had only a low level of damage

For the late second sowing, in order to estimate root yield per plot, a representative sub-sample was taken from each plot; either 16 roots, or a quarter of the roots retrieved, whichever was greater. Where plots had had fewer than 16 roots in total, all roots were included. The wet weight of each subsample was recorded (in addition to the wet weight of all the roots in the plot), roots were then sliced into cross sections no more than 5 mm in width and dried in an oven at 100˚C for seven days before being re-weighed to obtain dry mass for each subsample.

Variables analysed were: estimated crop yield (second sowing), the percentage of carrots undamaged by carrot fly and , damage severity. and estimated crop yield (late sowing).

Statistical analysis was conducted in GenStat (VSN International, 2017).~~ with some graphs being produced in RStudio (RStudio, 2016). ~~For data meeting parametric analysis assumptions, one way ANOVAs or chi-squared tests were performed and, where data were not normally distributed, they were transformed appropriately; percentage of undamaged roots were transformed to logits and severity transformed to logarithms~~.~~ Interaction between treatment and sowing was included as an effect and, where no significant interaction was found, mean values are presented over ~~early~~first and second~~late~~ sowings. For each variable, interactions between treatment and sowing were tested for and, if found, would have been analysed separately.

Results

There was no significant effect of distance from the hedge and carrot fly source on the percentage of undamaged carrots in either the first~~early~~ sowing (X^2=1.71, df=3, p>0.5) or the ~~late~~ second sowing (X^2=0.65, df=3, p<0.5). There was no significant effect of distance from the hedge and carrot fly source on damage severity for either the ~~early~~ first sowing (χ^2 = 0.55, 3 df, p > 0.05) or the ~~late~~ second sowing ($F_{3, 36}$ = 0.805, p > 0.05).

The estimated crop yield (only calculated for carrots harvested from the ~~the 2^nd^~~ second ~~harvest~~sowing) differed significantly between the treatments ($F_{4, 28}$ = 5.01, p = 0.004) (Table 1~~2~~). Plots unprotected by a barrier produced the lowest estimated crop yield. Plots protected by 60 cm barriers had increased production when compared to unprotected plots, whilst those protected by a 60 cm barrier with the addition of an overhang produced a larger estimated crop yield, similar to that produced in plots surrounded by a 90 cm barrier.

For percentage undamaged roots and severity, there was no significant interaction between treatment and sowing (in both cases, F4,63<2.5, P>0.05) and therefore mean values are over first and second sowings.

The percentage of undamaged roots differed significantly between treatments ($F_{4,35}$=23.5, p<0.001) (Table 1~~2~~). Plots protected by any of the three barrier treatments produced a higher percentage of undamaged roots than those unprotected by a barrier, but none produced a comparable percentage of undamaged carrots to those plots completely covered in insect-proof netting.

The severity (i.e. average damage score seen on damaged carrots in each plot) varied significantly with treatment ($F_{4,35}$=12.1, p<0.001) (Table 1~~2~~). The average level of damage seen on fly-attacked carrots was similar between unprotected plots and those protected by the shortest barrier (60 cm). Plots protected by the 60 cm barriers with an overhang and the taller 90 cm barriers had lower levels of damage. None of the barrier methods, however, came close to the protection afforded by completely covering the carrots with insect-proof netting.

~~How the percentage of undamaged carrots and the damage severity was affected by treatment is summarised visually for the early sowing in Figure 1a and the late sowing in Figure 1b.~~

Discussion

~~Two measures were used to quantify the level of damage by carrot fly in plots protected by the different barrier methods. Firstly the proportion of harvested carrots that were undamaged by carrot fly (after Jukes *et al*, 2016) was calculated for each plot. Carrots that are completely undamaged by carrot fly may be considered by gardeners to be highly preferable when compared to even those damaged to a low degree. This is because any carrot fly damage will affect, not only the aesthetic appeal of a carrot, but will also affect storage, meaning that they must be eaten before secondary rots set in. Roots attacked by carrot fly are also more susceptible to frost damage than undamaged carrots (Petherbridge *et al*, 1942). The second, complementary, measure used was damage severity. This is the mean damage score of all the damaged carrots in a plot. A low severity score would indicate that, of the carrots that were damaged, this damage was generally of a low level. In this experiment a barrier treatment can be considered to have been more successful than another if it has a higher proportion of undamaged carrots and a lower severity score. This would mean that few carrots were damaged and, those that were, had only a low level of damage~~

In both measures used to quantify damage by carrot fly, damage levels were greater in carrots harvested from the second ~~harvest~~ sowing than ~~in the first harvest~~from the first (see Figures 1a and 1b). This is likely to be because damage to this second sowing of carrots occurred not only due to the maggots laid by second generation flies that managed to overcome the barrier defences and enter the plots, but also from eggs laid by flies that emerged within the barriers i.e. the offspring of those that had entered the plots earlier in the season (Collier & Finch, 2009). This means that when using barriers, damage from carrot fly is usually greater after the second or third generation, where one occurs (Collier & Finch, 2009). This underlines the importance for gardeners to practice crop rotation when using barriers or covers.

The proportion of undamaged carrots harvested from uncovered plots in roots from the first sowing~~harvest~~ varied from around 0.6 to 1.0 (Figure 1a) suggesting that, in some cases, gardeners might be able to achieve an acceptable harvest without protecting crops but, with a mean undamaged proportion of 0.81 roots and a minimum of 0.6, this is not always the case and gardeners must be prepared to accept the risk of losing almost half a carrot crop if they do nothing to protect it from carrot fly. The level of damage seen in a particular plot is also likely to depend on the season's weather conditions, proximity of the plot to other carrot growing sites and occurrence of alternative host plants and the resulting size of the local carrot fly population. It should also be noted that this experiment took place on plots where no carrots had been grown previously and not close to any other carrot crops. It is therefore likely that the damage levels seen here will underestimate those likely in gardens or allotments where carrots are grown regularly.

It has been shown in previous studies of carrot fly biology that non-crop habitats such as hedgerows around carrot fields can provide shelter for, and allow aggregation of, carrot fly resulting in extensive damage to adjacent carrots (Baker, Ketteringham, Bray & White, 1942; Barnes, 1942; Petherbridge & Wright, 1943; Wainhouse & Coaker, 1981). Based on this previous research it was expected that in this study the distance of the carrot plots from the adjacent hedge would affect the amount of carrot fly damage. This was not the case, however, and there was no significant relationship between distance from the hedge and either the percentage of undamaged carrots or the severity of damaged of affected carrots although, had there been such a relationship, it would have been accounted for between treatments by the experimental blocking. The most likely explanation of this unexpected result may relate to the relatively small spatial scale of the study. Most previous studies, even those considered 'small-scale', have examined the effects of carrot fly over areas much larger than the current study. Fox Wilson (1945) for example, noted a higher proportion of unsaleable roots in rows near to hedges when compared to those further away but the beds extended 28 m from the hedge. Wright & Ashby (1946) noted a similar 'headland effect' between the headlands and an area approximately 27 m from the hedge, which was defined as 'midfield'. The experimental area in this study only extended approximately 15 m away from the hedge and so it is perhaps not surprising that, in this case, the distance from the hedge did not produce a significant effect on the levels of carrot fly damage. This experiment was most likely simply too small to see these differences but, if this is the case, then the majority of UK gardens are also too small. The average garden size in Great Britain is 14 m^2 (Horticultural Trade Association, 2018). In garden settings therefore, there is unlikely to be enough space to avoid the effects of a boundary fence or hedge on a carrot plot. Gardeners should be reassured that their placement of carrot plots with respect to boundary fences should not, in ordinary circumstances, make a difference to the damage levels they experience. This also demonstrates the value of matching the scale of a study to that of the relevant system as, in this case, conclusions reached from large scale studies of commercial production may be unhelpful to domestic production.

The likely reasons behind the yield differences between treatments are probably a combination of poor seedling emergence and/ or early carrot fly attack leading to a difference in carrot yield (as measured by the dry mass of harvested carrots from the late second sowing). Yield was increased by covering the carrots and by some of the barrier treatments when compared to plots with no barrier (Table 12).

-There are two likely explanations for this effect of barriers. Firstly, .A second factor that may have contributed to the comparatively greater yield harvested from the plots that were covered, had a 90 cm barrier or the 60 cm barrier with an overhang, as compared to the uncovered crops is early attack by carrot fly. When carrot flies lay eggs in clumps around seedlings the resulting maggots can destroy or seriously damage the plant's tap root leading to the death of many plants (Ellis *et al.*, 1987). Uncovered plots which had less protection from carrot fly may have lost more roots early in the season leading to the resulting lower numbers of carrots harvested and contributing to the lower yield in these plots.

~~Firstly barriers~~Secondly barriers can influence the microclimate around the crop, reducing wind speed and evapotranspiration and therefore water stress, as well as altering the air and soil temperature (Skidmore, Jacobs, & Hagen, 1972). In the case of winter wheat (*Triticum aestivum* L.) for example, plants sheltered by a slat-fence wind barrier grew taller, had larger leaves, and suffered less from water-stress when compared with those in an open field (Skidmore, Hagen, & Naylor, 1974). Carrot yields are known to be negatively correlated with increasing water stress (Reid & Gillespie, 2017) especially when this water stress occurs at the seedling emergence stage (Schmidhalter & Oertli, 1991).

~~A second factor that may have contributed to the comparatively greater yield harvested from the plots that were covered, had a 90 cm barrier or the 60 cm barrier with an overhang, as compared to the uncovered crops is early attack by carrot fly. When carrot flies lay eggs in clumps around seedlings the resulting maggots can destroy or seriously damage the plant's tap root leading to the death of many plants (Ellis *et al*., 1987). Uncovered plots which had less protection from carrot fly may have lost more roots early in the season leading to the resulting lower numbers of carrots harvested and contributing to the lower yield in these plots.~~

It is difficult from these data to ascertain the relative contribution of the effects of barrier shelter and carrot fly attack on the differing carrot yields from the plots. However, the plots were well irrigated when the weather was dry and the hedge running along the north of the plots is likely to have given some shelter against the prevailing south-west winds. Moreover, the patterns of yield and the numbers of harvested carrots follow roughly the same pattern as damage levels. Finally, the yield from plots protected by a 60 cm barrier with an overhang was greater than that from those plots with a 60 cm barrier alone and the overhang is unlikely to have caused much of an increase in shelter but is known to provide addition protection against the fly (Bomford et al., 2000) it therefore seems likely that early season carrot fly attack may have been the main contributing factor. Regardless of the reason however, improved yield would be of interest to carrot growers and so this information could be used to make more informed decisions regarding barrier choice and whether ~~or not~~ to completely cover the plots.

In conclusion the best option for reducing damage levels, both in terms of the percentage of carrots damaged and the damage levels those carrots are subject to, is to completely cover plots with insect-proof netting. This is of greater importance for carrots that will be harvested later in the season (or potentially in areas where the risk of infestation is higher than that encountered in our study). It should be noted that garden crop rotation practices must still be employed given that even completely covering the crops did not provide total protection, allowing carrot fly of successive generations to emerge within the covering if crops are not rotated.

Our study was conducted on one site and over one field season and so some caution must be adopted in using the results to generalise to all garden sites. From the results however we recommend that,

~~I~~if carrot growers are willing to accept some level of carrot fly attack, are planning to harvest their carrots early and/or live in an area where this pest has not previously been a problem then they could choose to install barriers, with the 90 cm and 60 cm with an overhang.~~-~~ These barriers provide~~ing~~ some protection when compared to no barriers at all, whilst also being easier to install and garden within when compared to completely covered plots. The percentage of carrots damaged and damage severity levels encountered within the plots protected by the 60 cm barrier was significantly higher than for the completely covered treatment; the levels of damage these carrots received was not significantly different to installing no barrier, so may not be worth the effort for gardeners.

Given the prevalence of information recommending 60 cm barriers as offering sufficient protection, efforts now need to be made to update advice in the light of these results and to recommend to home gardeners a combination of crop rotation with completely covering carrot crops rather than the currently recommended 60 cm barrier fences.

Conflict of interest statement

The authors have no conflicts of interest to disclose.

Author contribution

- Author 1, author 5 and author 6 conceived research.
- Author 1, author 2 and author 3 conducted experiments.
- Author 1, author 2 and author 4 analysed data and conducted statistical analyses.
- Author 2 produced the graphical figures
- Author 1 wrote the manuscript.
- Author 6 secured funding.
- All authors read and approved the manuscript.

Data availability statement

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

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Table and figure legends

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

Table 1~~2~~. Estimated plot dry mass (i.e. crop yield), percentage of undamaged roots per plot and Severity (i.e. average damage score seen on damaged carrots in each plot). For percentage undamaged roots and severity, there was no significant interaction between treatment and sowing (in both cases, F4,63<2.5, P>0.05) ~~Interaction between treatment and sowing included as an effect but no significant interaction was found~~ and therefore mean values are over first~~early~~ and ~~late~~ second sowings. *F* and *P* values apply to treatment effects.

~~**Figure 1a.** Cumulative stacked bar charts of the percentage of carrot roots assigned to each damage severity level (bright orange = damage level 0, through to black = damage level 5) for each of the treatments (no barrier, 60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and covered) for the early sowing. Error bars plotted using the standard error.~~

~~**Figure 1b.** Cumulative stacked bar charts of the percentage of carrot roots assigned to each damage severity level (bright orange = damage level 0, through to black = damage level 5) for each of the treatments (no barrier, 60 cm barrier, 60 cm barrier with an overhang, 90 cm barrier and covered) for the late sowing. Error bars plotted using the standard error.~~

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	