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ORIGINAL ARTICLE

Effects of insect net coverage in field vegetables on pests, diseases, natural enemies, and yield

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Abstract
With the reduced availability of effective plant protection products, alternative control measures gain importance. Insect net covers are a promising tool in this regard, because they can reduce pest damage on crop by exclusion of pests. However, as under practical conditions, most crop net covers need to be removed several times during a crop cycle to manage weeds and apply fertilizers, a complete exclusion of pests is not always feasible. In addition, net covers also have an impact on natural enemies, on microclimate, and may cause direct crop damage due to their tracking weight. Therefore, effects of net applications have to be assessed accordingly, depending on the specific crops and pests. In the current paper, effects on pests, on yield, and on the occurrence of diseases are assessed in Chinese cabbage, carrot, and leek. Whereas control of *Delia radicum*, *Phyllotreta* spp. and thrips was enhanced, aphids and mining flies showed increased population build ups and caused higher damages under net cover once they had been able to invade. Some plant diseases such as *Puccinia* spp. and *Alternaria* spp. did increase under the net covers. Pitfall trap catches in carrots and Chinese cabbage were lower in almost all natural enemy groups monitored under net covers as compared to open field plots. Yield was higher with net coverage in case of Chinese cabbage and leek, but not in carrot. Results are discussed and take into account the exclusion of natural enemies and measured changes in microclimate and photosynthetically active radiation.

Keywords Pitfall trap · Insect net · Cultivation guard net · Crop cover · Natural enemies · Microclimate

Introduction

Control of pests in vegetables increasingly becomes a challenge due to pest resistance, reduced availability of effective plant protection products, increased invasion of new pest species, and decreased development time of pests with higher mean temperatures due to climate change. As a result, effective alternative control measures gain importance. One of the most promising methods is the coverage of field crops with insect nets, because the coverage potentially can perform full protection of the crop from invading pests. However, because in most crops, the nets must be removed to manage weeds and to apply fertilizer, a complete exclusion of pests is not always feasible. In addition, development of pests from belowground developmental stages beneath the covered area and infested seedlings set limitations to this kind of protection. Because natural enemies are also excluded (Dib et al. 2010), invasion of pests under net covers can potentially cause increased population build up.

On the other hand, the net cover does not only have a direct exclusion effect due to the mesh size. It can be expected that net coverage depending on mesh size furthermore forms a visual barrier that can impede pests finding a host plant. Even if the host is located in the first place, insects are subsequently forced to land on the net material, which could result in a further take off if the material is categorized as a non-host by probing. For instance, nets for hail protection were shown to reduce the invasion of *Cydia pomonella* and *Adoxophyes orana* into apple orchards (Graf et al. 1999), additionally, Tasin et al. (2008) found that mating behavior was disrupted in *C. pomonella* below these nets.

Netting does also cause changes in the microclimate (Lee et al. 2009; Gogo et al. 2014; Simon et al. 2014), and changes in relative humidity can potentially cause phytosanitary problems with regard to pathogens. On the other

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hand, an expectable temperature increase can promote plant growth, whereas the likewise expectable reduction in photosynthetically active radiation (PAR) can reduce photosynthesis and consequently plant growth. Plants react differently to these changes in microclimate. For instance, covering French beans with insect nets had positive effects on seedling emergence, development time, pod yield, and quality (Gogo et al. 2014).

Nets are also not selective regarding invasion of natural enemies, as the exclusion is related to mesh size. Significant reductions in natural enemies under net coverage were already shown by Ludwig and Meyhöfer (2016).

In order to study the various effects on vegetable field crops, three vegetable crops of different plant families and growth types were chosen as model crops to be tested in field experiments: carrot, leek, and Chinese cabbage. Nets were chosen in order to exclude the main pests of the respective crop. These were for carrots the carrot fly *Chaemaepsila rosae*, for Chinese cabbage flea beetles *Phyllotreta* spp*.,* the cabbage root fly *Delia radicum*, and aphids. For leek, the focus was on the onion thrips *Thrips tabaci*. Other pests and pathogens as well as relative humidity, temperature, PAR, and yield effects were monitored. Nets were removed for management of weeds and fertilization. For carrot and Chinese cabbage, two different timings were chosen to increase the chance of observing differences in invading pest numbers.

The main objectives of this study were to study the effects of insect net coverage on relevant pests on different vegetables. It was tested if different timings for removing nets have effects on the development of pests under the net cover. It is assumed that effects may be different depending on reproduction rates and number of generations of pests, and natural enemies excluded by the net cover.

Methods

Trial design

Field trials in all crops were carried out in 2019 and 2020, with carrot (*Daucus carota* subsp. *Sativus*, variety "Nerac"), Chinese cabbage (*Brassica rapa* subsp. *Pekinensis*, variety "Spinkin"), and leek (*Allium ampeloprasum*, leek group, variety "Savel" used in 2019, variety "Galvani" used in 2020). Plot size was 4.5*4.5 m in all trials with four replicates set up in a randomized block design. In leek, only three replicates were carried out in 2019, but four in 2020. Carrot was sown with 5 cm distance in row and 40 cm between rows. Chinese cabbage was planted with 40 cm distance in row and 50 cm between rows, and leek was planted with 25 cm distance in row and 40 cm distance between rows. Plots were divided into two beds by a 60 cm way and assessment plants were taken from plants located in the center zone of each bed randomly in all cases.

In carrot and Chinese cabbage, a polyethylene net of 0.8 mm mesh size and a weight of 68 g/m^2 was used in trials (HADI GmbH, Germany) (Net0.8). In leek, a polyamide net with a mesh size of 0.35 mm and a weight of 25 g/m^2 was used (BIOTHRIPS 346, MDB Texinov, France) (Net0.35). For Chinese cabbage and carrot, the removing dates of nets were linked to the flight activity of *P. rosae* or *D. radicum*, respectively, by the SWAT-Model (Gebelein et al. 2001), and nets were removed for four hours in the morning. For leek, nets were only removed shortly for crop fertilization and weed control. An overview of treatments in the different crops and years is given in Table 1. Growing period, removing dates and PPP application times of all treatments, and years are summarized in Table 2.

Plants used for assessments were chosen randomly in the core part of each plot, omitting the outer plants. For carrot, 50 plants were pooled per replicate and used for weight and damage assessments during harvest. For cabbage, fifteen cabbage heads per replicate were assessed separately for pest damage and weight during harvest per replicate in 2019. The number was reduced to five cabbage heads per replicate in 2020. For leek, 10 plants per replicate were assessed separately for damage and weight during harvest in both years.

Intermediate assessments were carried out non-destructively directly in field plots, for *Alternaria* spp. spots on carrot leaves in 2019 on 50 plants, and for aphid counts on Chinese cabbage in 2020 on 20 plants per replicate.

In most cases, plant damage was assessed visually on leaves and/or roots. For *Delia radicum*, damage was examined by cutting of the lower part of the cabbage head and assessing the percent damaged area in 2019. In order to rather detect number of attacks than severity, in 2020, the number of feeding tunnels was counted.

In 2020, thrips numbers were assessed by destructive sampling of four plants per replicate in the laboratory at each of the three assessment dates. Single plants were taken directly from the field into single zipped plastic bags. Plants were frozen, then unfrozen and leaves were separated, water with 0.01% of washing liquid was added (250 ml for young plants, 500 ml for older plants) and bags were shaken for about 1 min. Then, leaves were taken out and rinsed with water above the bag. Liquid was given through a fine sieve or directly through a filter paper, and thrips numbers including adults and larvae were counted.

Pitfall traps

Pitfall traps were installed in 2019 and 2020 in the open field treatments (Control, PPP Control), and one net covered treatment (Net CoverP). One transparent plastic cup (diameter 9 cm, height 10 cm, volume 400 ml) was embedded to

Table 1 Overview of treatments carried out per crop and year

Crop	Year	Net	Treatment description	Abbreviation
Chinese cabbage	2019 & 2020	Net0.8	Net coverage, removed in accordance to predicted peaks of flight activity for the species of *D. radicum* by SWAT	NetCoverP
			Net coverage, removed in accordance to predicted valleys of flight activity for the species of *D. radicum* by SWAT	NetCoverV
			Uncovered control where plant protection products were applied according to common damage thresholds	PPP Control
	2020		Untreated control	Control
Carrot	2019 & 2020	Net0.8	Net coverage, removed in accordance to predicted peaks of flight activity for the species of *P. rosae* by SWAT	NetCoverP
			Net coverage, removed in accordance to predicted valleys of flight activity for the species of *P. rosae* by SWAT	NetCoverV
			Uncovered control where plant protection products were applied according to common damage thresholds	PPP Control
	2020		Untreated control	Control
Leek	2019 & 2020	Net0.35	Net coverage, removed only for about 30 min per replicate to carry out necessary fertilization and weed management	NetCover
			Uncovered control with regular application against thrips, as no established threshold was available	PPP Control
	2019	Net0.8	Untreated control covered with Net0.8 to check for effects on plants by coverage with different net types	CovControl
	2020		Untreated control	Control

SWAT refers to usage of the SWAT-Model (Gebelein et al. 2001)

the soil centrally into each replicate. Cups were embedded with the upper margin ending at ground level and were filled with 200 ml of benzoic acid solution. The solution was produced by solving 75 g bencoic acid in 3 l of hot water under constant mixing in the first step, and then a further dilution by adding hot water up to a total volume of 9 l. Cups were protected from rain and sun by a terracotta colored plastic saucer with a diameter of 14 cm installed about 3 cm above ground. A drop of diluted detergent was added to each cup. Cups were replaced monthly during cropping season, and trapped arthopods were sieved from the liquid and assessed under the stereo microscope. All counts were summed up per season, replicate, and arthropod group (carabids, ladybirds, rove beetles, and spiders).

Climate data

Temperature and relative humidity were assessed using data loggers (Tinytag Plus 2, Gemini Data Loggers, Chichester, UK) during both years in Chinese cabbage and carrot, and in 2020 also in leek. One logger was installed per replicate, fixed on a wooden stick just above the crop. On the same stick, a terracotta colored plastic saucer with a diameter of 14 cm was fixed above each logger in a distance of approximately 5 cm. The saucer was installed for shading the logger, and in case of net coverage, to avoid direct contact of data logger and net. The mean, minimum and maximum values for the measuring timespan were calculated based on all logger values together. For the measures in Chinese cabbage and carrot, always the PPP control was taken as representative of the uncovered treatment, and the Net CoverV was taken as representative of the net covered treatment. In leek 2020, the Net Cover treatment was used instead.

A LI-1500 Logger (LI-COR Environmental, US) with two sensors to log PAR was used in the experiments in 2020. One sensor was placed in the open field, the other below the respective net, but above the respective crop. Both sensors were fixed at similar heights. Data were collected at two days to cover sunny and cloudy weather conditions, between maximum 9 am to 4 pm. The mean, minimum and maximum values of PAR for the full measured timespan were calculated.

Data analysis

The effect of different cultivation methods (use of nets, PPP, control) on yield was examined by fitting linear mixed-effects models, using the REML (Restricted Maximum Likelihood) criterion. In order to increase the fit of the model, the square root was taken from the data within these analyses. For count data of pest species, a generalized linear mixed model (GLMM) with Poisson distribution was applied first, but due to overdispersion in all cases, a GLMM with negative binomial distribution was used instead. For wet rot in Chinese cabbage, where only "yes" or "no" for symptoms was assessed, a GLMM with binomial distribution was applied.

Table 2 Summary of dates when net was removed (grey) and PPP applications, for carrot (a), Chinese cabbage (b) and leek (c)

a

Carrot

2019 (planting: Apr 2, harvest: Sep 24)			2020 (planting: Mar 19, harvest: Oct 5)			
PPP Control	**Net CoverP**	**Net CoverV**	**Control**	**PPP Control**	**Net CoverP**	**Net CoverV**
			Mar 19, Pendimethaline[1]			
Apr 4, Pendimethaline[1]						
	Apr24					
					May5	
					May8	
	May10					
	May21					
						Jun3
			Jun3, Metribuzine[1]			
		Jun7				
						Jun8
		Jun17				
				Jun25, Cyantraniliprole[1]		
	Jul2			Jul2, Cyantraniliprole[1]		
					Jul9	
					Jul14	
		Jul19				
						Aug5
						Aug6
			Aug 6, Difenoconazole + Azoxystrobine[1]			
		Aug2				

b

Chinese cabbage

2019 (planting: June 4, harvest: July 31)			2020 (planting: May 26, harvest: July 21)			
PPP Control	**Net CoverP**	**Net CoverV**	**Control**	**PPP Control**	**Net CoverP**	**Net CoverV**
Jun3, Pendimethaline[1]						
			Mar29, Pendimethaline[1]			
			May25, Pendimethaline[1]			
				May25, Spinosad[1,3]		
Jun14, Spinosad[1,3]						
					Jun15	
					Jun16	
	Jun17				Jun17	
Jun24, Thiacloprid[1]	Jun24					
						Jun29
						Jun30
Jul1, lambda-Cyhalothrine[1]						
						Jul2
		Jul3				
Jul8, Thiacloprid[1]						
		Jul11				
Jul15, lambda-Cyhalothrine[1]						
		Jul18				
Jul25, Spirotetramate[1]; Difenoconazole + Azoxystrobine[1]						
	Jul26					

Table 2 (continued)

c

Leek[2]					
2019 (planting: Jun 13, harvest Oct 17)			2020 (planting: Jun 10, harvest: Sept 23)		
Control	PPP Control	NetCover	Control	PPP Control	NetCover
				Jul8, Pendimethaline[1]	
	Jun17, Spinosad[1]				
	Jun24, lambda-Cyhalothrine[1]				
	Jul2, Spinosad[1]				
	Jul8, Spinosad[1]				
	Jul15, Thiacloprid[1]				
	Jul23, Spinosad[1]				
	Jul29, Thiacloprid[1]				
	Aug8, Pyridat[1]				
				Aug6, lambda-Cyhalothrine[1]	
	Aug7, Spinosad[1]				
					Aug12
	Aug13, lambda-Cyhalothrine[1]			Aug13, Spinosad[1]	
	Aug20, Spinosad[1]			Aug20, Thiacloprid[1]	
	Aug27, Thiacloprid[1]			Aug27, Spinosad[1]	
				Sep3, Thiacloprid[1]	
				Sep10, Spinosad[1]	Sep10
				Sep17, Thiacloprid[1]	

[1]Active ingredience = product + application rate: Pendimethaline = StompAqua 3,5 l/ha; Metribuzine = Sencor Liquid 3 l/ha; Cyantraniliprole = Minecto One 187,5 g/ha; Difenoconazole + Azoxystrobine = ASKON 1 l/ha; Spinosad = SpinTor 12 ml/1000 plants; Thiacloprid = Calypso 0,12 l/ha; lambda-Cyhalothrine = Karate Zeon 0,075 l/ha (Jul15, 2019 = Bulldock Top 0,3 l/ha); Spirotetramate = Movento OD 150 0,48 l/ha, Pyridat = Lentagran 2 kg/ha

[2]In leek, all PPP except herbicides with 0.01% BreakThru

[3]Drench application

All these procedures were carried out using the lme4 package (Bates et al. 2015). Whenever a percentage of damaged area was assessed, a GLMM with beta distribution was applied, using the glmmTMB package (Brooks et al. 2017). All natural enemy count data were analyzed using the lme4 package, by fitting GLMMs with Poisson distribution.

All model structures included the treatment as fixed effect and the interaction of year and replicate as random effect. For results that included one year only, a generalized linear model (GLM) with block included as fixed effect was carried out, due to the limited degrees of freedom. Post hoc tests were carried out using the emmeans package (Lenth 2021) by comparison of the estimated marginal means (EMMs).

All statistical analyses were carried out with R (R Core Team 2021). All graphics were plotted with ggplot2 (Wickham 2016).

Results

Carrot

Alternaria spp. infestation on roots was monitored during yield assessment in 2019 and 2020. In 2019, an additional assessment of *Alternaria spp.* infestation on leaves was carried out (Fig. 1). The infestation on leaves was significantly higher in both net cover treatments (Net CoverP: EMM = 22.7%, lCL = 20.5%, uCL = 25.0%; Net CoverV: EMM = 23.0%, lCL = 20.8%, uCL = 25.3%) as compared to the PPP Control (EMM = 15.2%, lCL = 13.5%, uCL = 17.1%), but not between net cover treatments (PPP Control/Net CoverP $p = < 0.0001$, PPP Control/Net CoverV $p = < 0.0001$, Net CoverP/Net CoverV $p = 0.9791$). However, there was almost no visible infestation of roots observed during yield assessments in any treatment (Control [only 2020]: EMM = 0.16%, lCL = 0.13%, uCL = 0.21%; PPP Control: EMM = 0.17%, lCL = 0.13%, uCL = 0.22%, Net CoverP: EMM = 0.18%, lCL = 0.14%, uCL = 0.23%, Net CoverV: EMM = 0.18%, lCL = 0.14%, uCL = 0.23%). Accordingly, there was no significant differences between any of the treatments regarding root infestation.

In 2020, there was a notable attack of aphids on the carrot leaves at early season (Fig. 2). Therefore, an intermediate assessment was carried out during the removing time of Net CoverV. The latter net treatment (EMM = 5.91, lCL = 4.01, uCL = 8.70) had significantly higher aphid numbers than both of the other uncovered treatments (Control: EMM = 0.70, lCL = 0.42, uCL = 1.18; PPP Control: EMM = 1.16, lCL = 0.73, uCL = 1.84) (Control/Net CoverV:

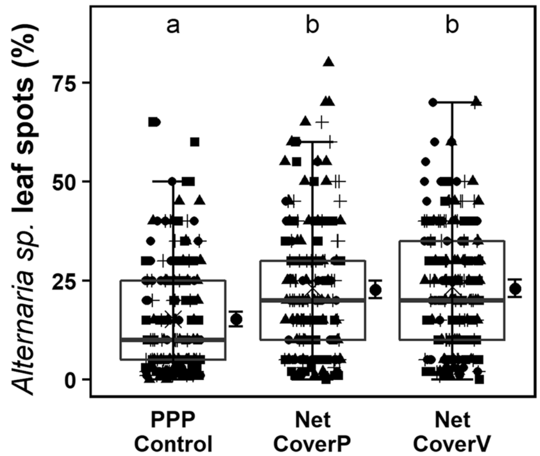

Fig. 1 *Alternaria* spp. Damage (leaf spots) on carrot leaves in an intermediate assessment August 27, 2019. Points represent rated plants. Point shape represents the replicate. Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

$p = < 0.0001$, PPP Control / Net CoverV: $p = < 0.0001$). Net CoverV and Net CoverP did not differ significantly ($p = 0.3297$). In both years, no relevant attack of *C. rosae* was observed.

Carrot yield was comparable in both years, and treatments (Control: EMM = 3,72 kg, lCL = 3.05 kg, uCL = 4.40 kg, PPP Control: EMM = 3.93 kg, lCL = 3,26 kg, uCL = 4,61 kg; Net CoverP: 4.39 kg, lCL = 3.72 kg, uCL = 5.07 kg; Net CoverV: 4.57 kg, lCL = 3.89 kg, uCL = 5.24 kg) did not differ significantly (Fig. 3).

Chinese cabbage

In Chinese cabbage, timing of the harvest is very important for a high-quality yield. As the optimal time slot is rather short, it was surpassed in 2019 and had high infestations of wet rot. For better estimation of this effect, an early and a late harvest was carried out in 2020. Comparing both harvests with high incidence of wet rot, the one in 2019 and the late one on Jul 21, 2020, the treatment PPP Control (EMM 78.2%, lCL = 65.1%, uCL = 87.3%) was significantly more often infested than the Net CoverP (EMM 57.8%, lCL = 43.2%, uCL = 71.1%, $p = 0.033$) and Net CoverV (EMM 58.4%, lCL = 43.8%, uCL = 71.7%, $p = 0.041$). The Control (EMM 60.4%, lCL 36.3%, uCL 80.3%) was not significantly different to any other treatment. However, with a good harvest timing like on Jun 30, 2020, nearly no infestation occurred in any treatment.

For *D. radicum*, no significant differences between treatments were detected in 2019, where a low attack was detected, rated in the percentage area attacked (data not shown). In 2020, a high attack was detected, rated in number of feeding tunnels (Fig. 4B). That year, both treatments with net cover (Net CoverP: EMM = 0.19, lCL = 0.07, uCL = 0.51; Net CoverV: EMM = 0.55, lCL = 0.30, uCL = 1.01) did show significantly lower numbers of feeding tunnels as compared to the Control (EMM = 10.58, lCL = 8.55, uCL = 13.08) and the PPP Control (EMM = 9.36, lCL = 7.52, uCL = 11.64) (for all comparisons $p = < 0.0001$). There were no significant

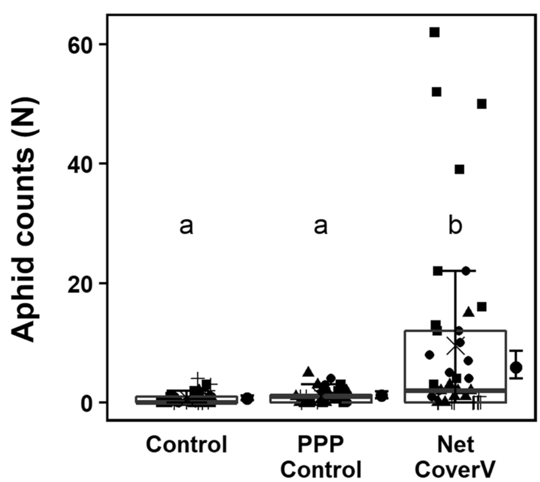

Fig. 2 Aphid numbers in an intermediate assessment on the carrot trial, June 3, 2020. Only the Net CoverV treatment was removed that date as scheduled and was rated together with both controls. Points represent rated plants. Point shape represents the replicate. Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

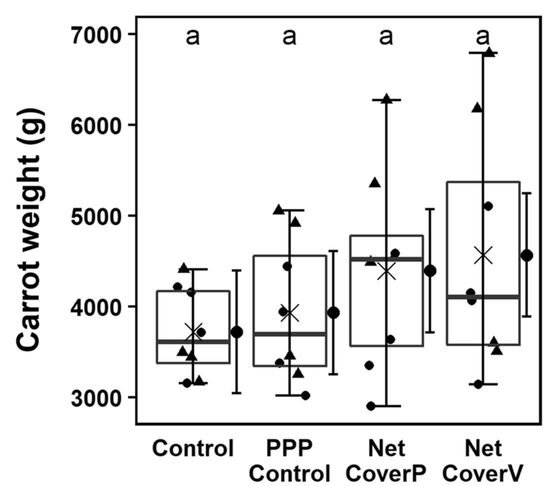

Fig. 3 Carrot yield in the trials of 2019 and 2020. Points represent batches of 50 carrots weighted together. Point shape represents the year (round = 2019, triangle = 2020). Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

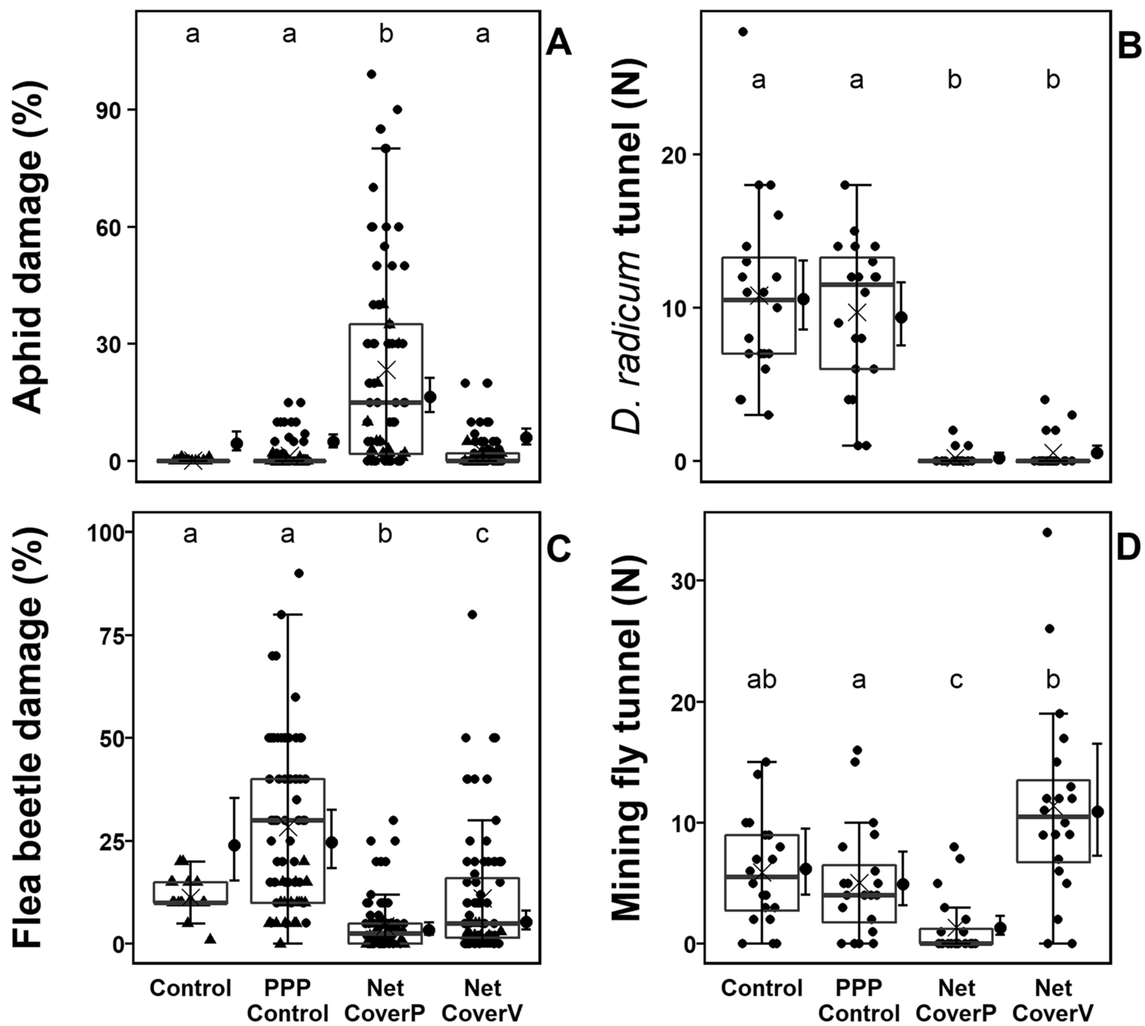

Fig. 4 Area covered by aphid colonies or their contaminants in 2019 and 2020 (**A**), number of feeding tunnel caused by *Delia radicum* in 2020 (**B**), feeding damage of flea beetles in 2019 and 2020 (**C**), and number of feeding tunnels from mining flies in 2020, in the Chinese cabbage yield assessments. The control treatment (Control) was only carried out in 2020. Points represent rated plants. Point shape represents the year (round = 2019, triangle = 2020). Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

differences between either covered treatments ($p = 0.3061$) or uncovered treatments ($p = 0.8589$). Damage by flea beetles was significantly reduced by both net covers (Net CoverP: EMM = 3.39%, lCL = 2.18%, uCL = 5.22%; Net CoverV: EMM = 5.39%, lCL = 3.55%, uCL = 8.08%) as compared to Control (EMM = 24.01%, lCL = 15.40%, uCL = 35.40%) and PPP Control (EMM = 24.77%, lCL = 18.34%, uCL = 32.54%) (Each comparison $p = < 0.0001$). Control and PPP Control did not differ significantly ($p = 0.989$). Although both net cover treatments showed low attack levels, the timing of the removings had a significant effect on the attack level ($p = 0.001$) (Fig. 4C). Contamination by aphid colonies was significantly increased in Net CoverP (EMM = 16.34%, lCL = 12.55%, uCL = 21.00%) as compared to all other treatments (Control: EMM = 4.65%, lCL = 2.82%, uCL = 7.56%; PPP Control: EMM = 5.03%, lCL = 3.67%, uCL = 6.87%; Net CoverV: EMM = 6.16%, lCL = 4.50%, uCL = 8.36%) (Each comparison $p = < 0.0001$). There were no significant differences between all other treatments (Fig. 4A). The number of mines caused by mining flies was significantly lower in Net CoverP (EMM = 1.33, lCL = 0.77, uCL = 2.29) as compared to the Control (EMM = 6.19, lCL = 4.04, uCL = 9.50, $p = 0.0001$), PPP Control (EMM = 4.93, lCL = 3.19, uCL = 7.63, $p = 0.0013$) and NetCoverV (EMM = 10.95, lCL = 7.25, uCL = 16.52, $p = < 0.0001$). At the same time, NetCoverV was significantly higher as compared to PPP Control ($p = 0.0455$). Mine counts in Control did not differ significantly from the counts in PPP Control ($p = 0.89$) or NetCoverV ($p = 0.2357$) (Fig. 4D). Damage by feeding of butterfly caterpillars was only significantly higher in the

PPP Control (EEM = 9.84%, lCL = 2.8%, uCL = 36.9%) as compared to the Net CoverP (EEM = 6.10%, lCL = 4.16%, uCL = 8.85%, $p = 0.0068$). As a technical remark, the higher EMMs as compared to the plotted data for the untreated control (Fig. 4A, Fig. 4C) can be explained by the overall lower level of infestations of the respective pests when this treatment was carried out in 2020, as compared to the trial in 2019 without this treatment.

Yield in Chinese cabbage weighted on Jul 30, 2019 and Jun 30, 2020 was significantly increased in both net covered treatments (Net CoverP: EMM = 1.11 kg, lCL = 0.94 kg, uCL = 1.30 kg; Net CoverV: EMM = 1.10 kg, lCL = 0.93 kg, uCL = 1.29 kg) as compared to both uncovered cultivated treatments (Control: EMM = 0.67 kg, lCL = 0.50 kg, uCL = 0.86 kg; PPP Control: EMM = 0.79 kg, lCL = 0.64 kg, uCL = 0.95 kg) (All comparisons: $p = < 0.0001$). Both net covered treatments as well as both uncovered treatments did not differ significantly in weight ($p = 0.9977$ and $p = 0.5255$, respectively) (Fig. 5).

Leek

Damaged area by *Puccinia* spp. was numerically low in both years. Damage level in 2019 was significantly lower in CovControl (EMM = 1.69%, lCL = 0.98%, uCL = 2.89%) and Net Cover (EMM = 2.28%, lCL = 1.36%, uCL = 3.80%) as compared to PPP Control (EMM = 4.36%, lCL = 2.77%, uCL = 6.79%) ($p = 0.0013$ and $p = < 0.0380$, respectively). CovControl was not significantly different from Net Cover ($p = 0.5065$) (Fig. 6A). Damage level in 2020 was significantly lower in Control (EMM = 0.41%, lCL = 0.18%, uCL = 0.91%) and PPP Control (EMM = 0.54%, lCL = 0.25%, uCL = 1.16%) as compared to Net Cover (EMM = 2.78%, lCL = 1.44%, uCL = 5.29%) (both comparisons $p < 0.0001$). Control was not significantly different from PPP Control ($p = 0.4894$) (Fig. 6B).

Thrips feeding damage on leek was numerically low in both years. Damage level in 2019 was lower in PPP Control (EMM = 3.0%, lCL = 2.4%, uCL = 3.7%) and Net Cover (EMM = 2.4%, lCL = 1.9%, uCL = 3.1%) as compared to CovControl (EMM = 5.0%, lCL = 4.2%, uCL = 5.9%) ($p = 0.0012$ and $p = < 0.0001$, respectively), but no difference was found between PPP Control and Net Cover ($p = 0.4585$) (Fig. 7A). In 2020, similarly, damage level was lower in PPP Control (EMM = 1.6%, lCL = 1.2%, uCL = 2.2%) and Net Cover (EMM = 1.9%, lCL = 1.4%, uCL = 2.6%) as compared to Control (EMM = 3.2%, lCL = 2.5%, uCL = 4.2%) ($p = < 0.0001$ and $p = 0.0001$, respectively), but again no difference was found between PPP Control and Net Cover ($p = 0.3818$) (Fig. 7B).

The actual numbers of thrips counted per leek plant in 2020 was significantly lower in Net Cover (Aug 04: EMM = 3.44, lCL = 2.43, uCL = 4.88; Sept 01: EMM = 5.21, lCL = 3.81, uCL = 7.13; Sept 21: EMM = 8.76, lCL = 6.61, uCL = 11.61) as compared to Control (Aug 04: EMM = 9.05,

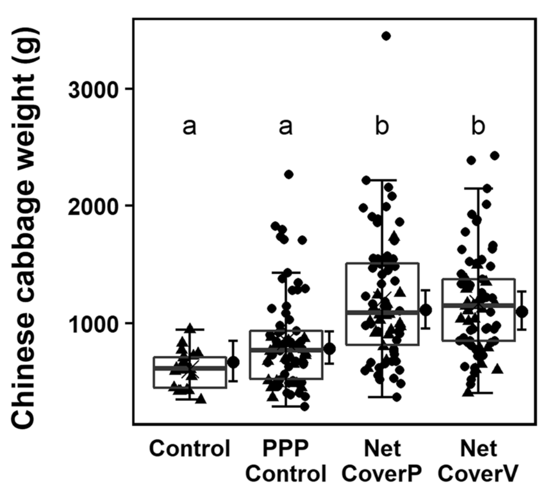

Fig. 5 Chinese cabbage yield in the trials of 2019 and 2020. Points represent weighted plants. Point shape represents the year (round = 2019, triangle = 2020). Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

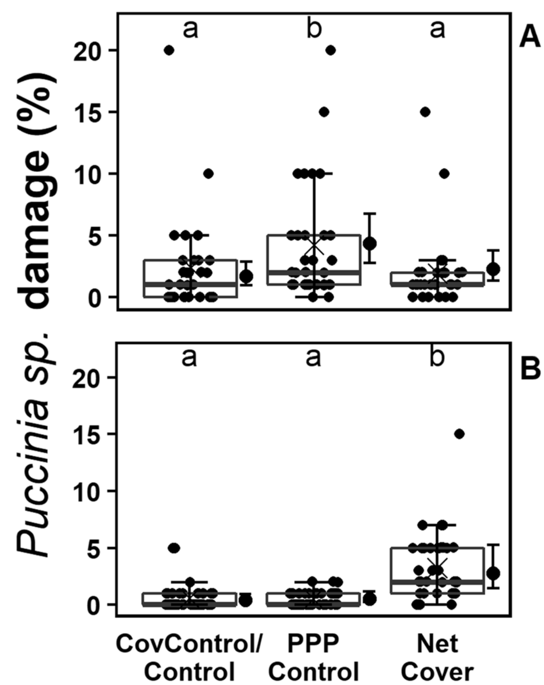

Fig. 6 Damaged area by *Puccinia* spp. infestation in leek in yield assessments. In 2019 (**A**) the untreated control was covered with Net0.8 (CovControl), in 2020 (**B**) a control without coverage was carried out instead (Control). Points represent rated plants. Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

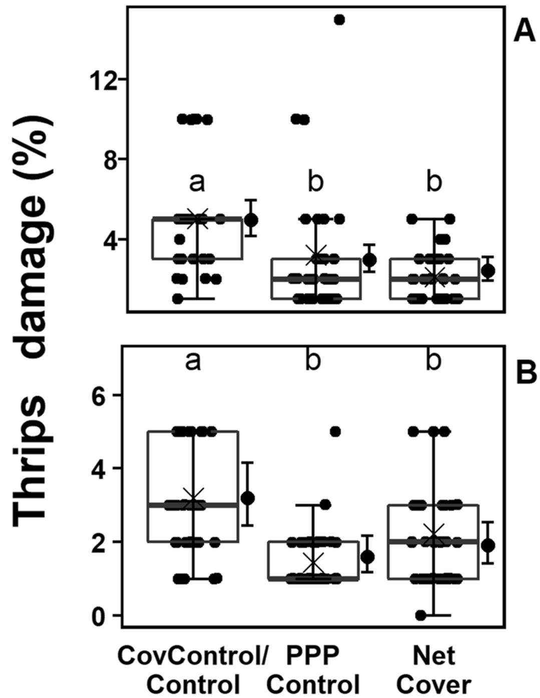

Fig. 7 Thrips feeding damage in leek in yield assessments. In 2019 (**A**) the untreated control was covered with Net0.8 (CovControl), in 2020 (**B**) a control without coverage was carried out instead (Control). Points represent rated plants. Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower Confidence interval at right side of each Boxplot

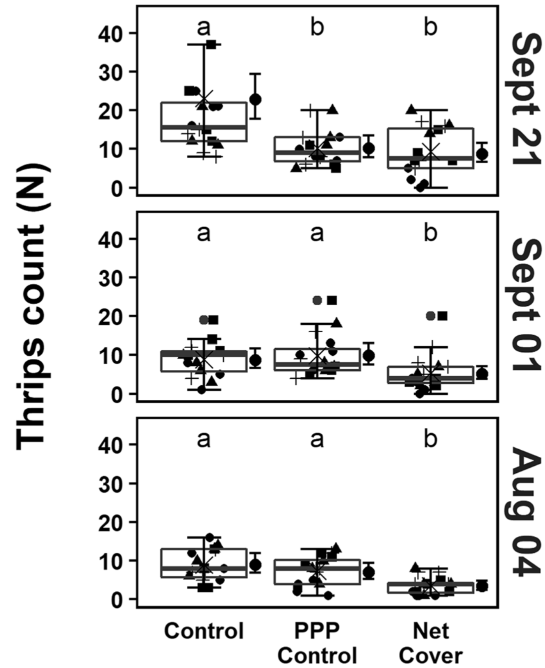

Fig. 8 Thrips numbers in leek at two intermediate assessments and at the time of yield in 2020. Points represent rated plants. Point shape represents the replicate. Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

lCL = 6.84, uCL = 11.98; Sept 01: EMM = 8.77, lCL = 6.61, uCL = 11.62; Sept 21: EMM = 22.84, lCL = 17.79, uCL = 29.33) for all three monitoring dates (Aug 04: $p = 0.0001$, Sept 1: $p = 0.0408$, Sept 21: $p = < 0.0001$). Counts in Net Cover were also lower as compared to PPP Control (Aug 04: EMM = 7.04, lCL = 5.25, uCL = 9.44; Sept 01: EMM = 9.90, lCL = 7.51, uCL = 13.04; Sept 21: EMM = 10.23, lCL = 7.77, uCL = 13.46) for the first two monitoring dates (Aug 04: $p = 0.0059$, Sept 1: $p = 0.0073$), but not the last date (Sept 21: $p = 0.7200$). At the last monitoring date, at time of harvest, also the counts in PPP Control were significantly lower as compared to Control (Sept 21: $p = 0.0001$), which was not the case for both previous dates (Aug 4: $p = 0.4449$, Sept 01: $p = 0.8189$) (Fig. 8).

Yield measured per plant in 2019, when the Control was covered with the Net0.8 (CovControl), no significant differences were found between the treatments (Fig. 9A). In 2020, when an uncovered Control was installed (Control), yield was significantly higher in Net Cover (EMM = 0.50 kg, lCL = 0.46 kg, uCL = 0.54 kg) as compared to Control (EMM = 0.39 kg, lCL = 0.36 kg, uCL = 0.43 kg) ($p = 0.004$), but not as compared to PPP Control (EMM = 0.45 kg, lCL = 0.42 kg, uCL = 0.49 kg) ($p = 0.2938$). PPP Control was not significantly different as compared to the Control ($p = 0.0552$) (Fig. 9B).

Effects of net covers on natural enemies

Numbers of natural enemies caught in pitfall traps in 2019 and 2020 were for most monitored groups significantly lower under net coverage as compared to open crop (Fig. 10).

In carrot, carabids were significantly lower in Net CoverP (EMM = 2.54, lCL = 1.48, uCL = 4.37) as compared to Control (EMM = 12.29, lCL = 7.29, uCL = 20.71) and PPP Control (EMM = 13.04, lCL = 8.73, uCL = 19.48) (both comparisons $p = < 0.0001$). Both open treatments showed no significant differences ($p = 0.9668$). Ladybirds were significantly lower in Net CoverP (EMM = 1.72, lCL = 0.963, uCL = 3.07) as compared to Control (EMM = 16.96, lCL = 11.20, uCL = 25.67) and PPP Control (EMM = 20.87, lCL = 15.12, uCL = 28.81) (both comparisons $p = < 0.0001$). Both open treatments showed no significant differences ($p = 0.4907$). Spiders were significantly lower in Net CoverP (EMM = 22.0, lCL = 15.6, uCL = 31.0) as compared to Control (EMM = 42.4, lCL = 29.3, uCL = 61.3) and PPP Control

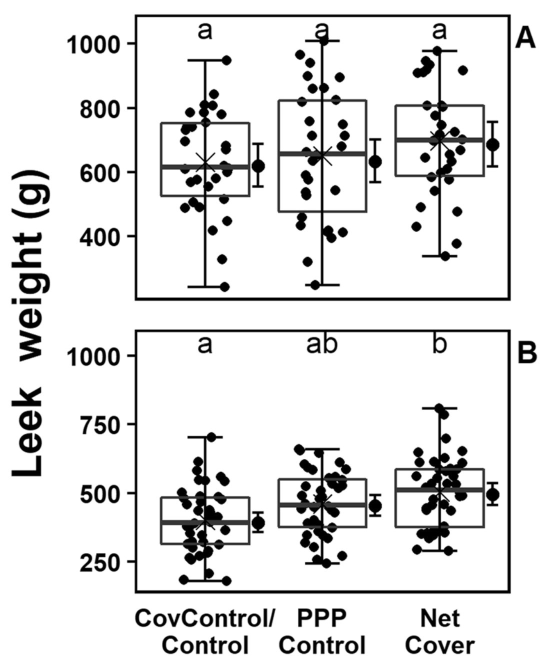

Fig. 9 Leek yield in assessments. In 2019 (**A**) the untreated control was covered with Net0.8 (CovControl), in 2020 (**B**) a control without coverage was carried out instead (Control). Points represent rated plants. Significant differences are indicated by different letters. Boxplots with additional mean value (cross). Estimated Marginal Mean with upper and lower limits of 95% confidence interval at right side of each Boxplot

(EMM = 55.0, lCL = 39.7, uCL = 76.2) (both comparisons $p = < 0.0001$). Both open treatments showed no significant differences ($p = 0.0705$). Rove Beetles were significantly lower in Net CoverP (EMM = 9.05, lCL = 6.18, uCL = 13.2) as compared to Control (EMM = 21.3, lCL = 15.67, uCL = 28.2) and PPP Control (EMM = 20.3, lCL = 15.08, uCL = 27.3) (both comparisons $p = 0.0001$). Both open treatments showed no significant differences ($p = 0.9709$).

In Chinese cabbage, no significant differences were found for carabids between Net CoverP (EMM = 5.56, lCL = 4.12, uCL = 7.51) as compared to Control (EMM = 4.51, lCL = 2.51, uCL = 8.13) ($p = 0.8186$) or PPP Control (EMM = 5.20, lCL = 3.82, uCL = 7.09) ($p = 0.9470$). Both open treatments showed also no significant differences ($p = 0.9118$). Ladybirds were significantly lower in Net CoverP (EMM = 1.34, lCL = 0.733, uCL = 2.43) as compared to Control (EMM = 7.09, lCL = 4.36, uCL = 11.52) ($p = < 0.0001$) and PPP Control (EMM = 6.68, lCL = 5.03, uCL = 8.87) ($p = < 0.0001$). Both open treatments showed no significant differences ($p = 0.9771$). Spiders were significantly lower in Net CoverP (EMM = 15.8, lCL = 12.7, uCL = 19.7) as compared to Control (EMM = 32.4, lCL = 24.3, uCL = 43.3) and PPP Control (EMM = 24.8, lCL = 20.4, uCL = 30.3) (both comparisons $p = < 0.0001$). Both open treatments showed no significant differences ($p = 0.2180$). Rove Beetles were significantly lower in Net CoverP (EMM = 16.3, lCL = 12.7, uCL = 20.8) as compared to Control (EMM = 34.2, lCL = 25.9, uCL = 45.3) and PPP Control (EMM = 67.9, lCL = 55.6, uCL = 82.9) (both comparisons $p = < 0.0001$). Additionally, rove beetle numbers in the Control were significantly lower as compared to PPP Control ($p = < 0.0001$).

Climate data

The average temperature below net cover was one degree higher under the Net0.35 in leek. Under the Net0.8 and irrespectively of the crop covered, differences were even smaller (Table 3). Also, the average RH was rather comparable in both treatments, only in the later season, for carrot, a 6% higher average RH was measured under the Net0.8. In leek, the measured average RH was about 5% lower under the Net0.35 (Table 3).

The Net0.8 reduced PAR by about 50%, whereas the Net0.35 reduced PAR only by about 30%. However, maximum and minimum PAR in the Net0.8 were similar to the uncovered field conditions, whereas maximum PAR under the Net0.35 was about 30% lower as compared to the uncovered field condition (Table 4).

Discussion

A net cover with 0.8 mm mesh for Chinese cabbage was effective against cabbage root fly and flea beetles (Fig. 4B, Fig. 4C). Similar results for flea beetles were shown by Hedrich and Rascher (2019). However, the net cover did not effectively inhibit attack of aphids and mining flies, and the level of attack depended strongly on net removing dates (Fig. 4A, Fig. 4D). Once the latter pests have entered the crop during removing times for management, their population development was even higher than in the uncovered crop. The same phenomenon was observed for carrots attacked by aphids (Fig. 2). Therefore, it seems likely that aphids and mining flies profit from changes in either microclimate under the net, or the exclusion of natural enemies, or both. However, also the expectable reduced wind speed and some shelter from hard rain under the net cover could reduce mortality of these rather small pest species. In a study of Fidelis et al. (2018), rain and physiological disturbance added to the mortality, although they were not the most important factors.

As a low difference in relative humidity and temperature was measured (Table 3), it seems more likely that the exclusion of natural enemies plays the key role here. Aphids have a fast development time and reproduction rate. For instance, development time of *Brevicoryne brassicae* was 8.9–10.4 days on different brassica crops and

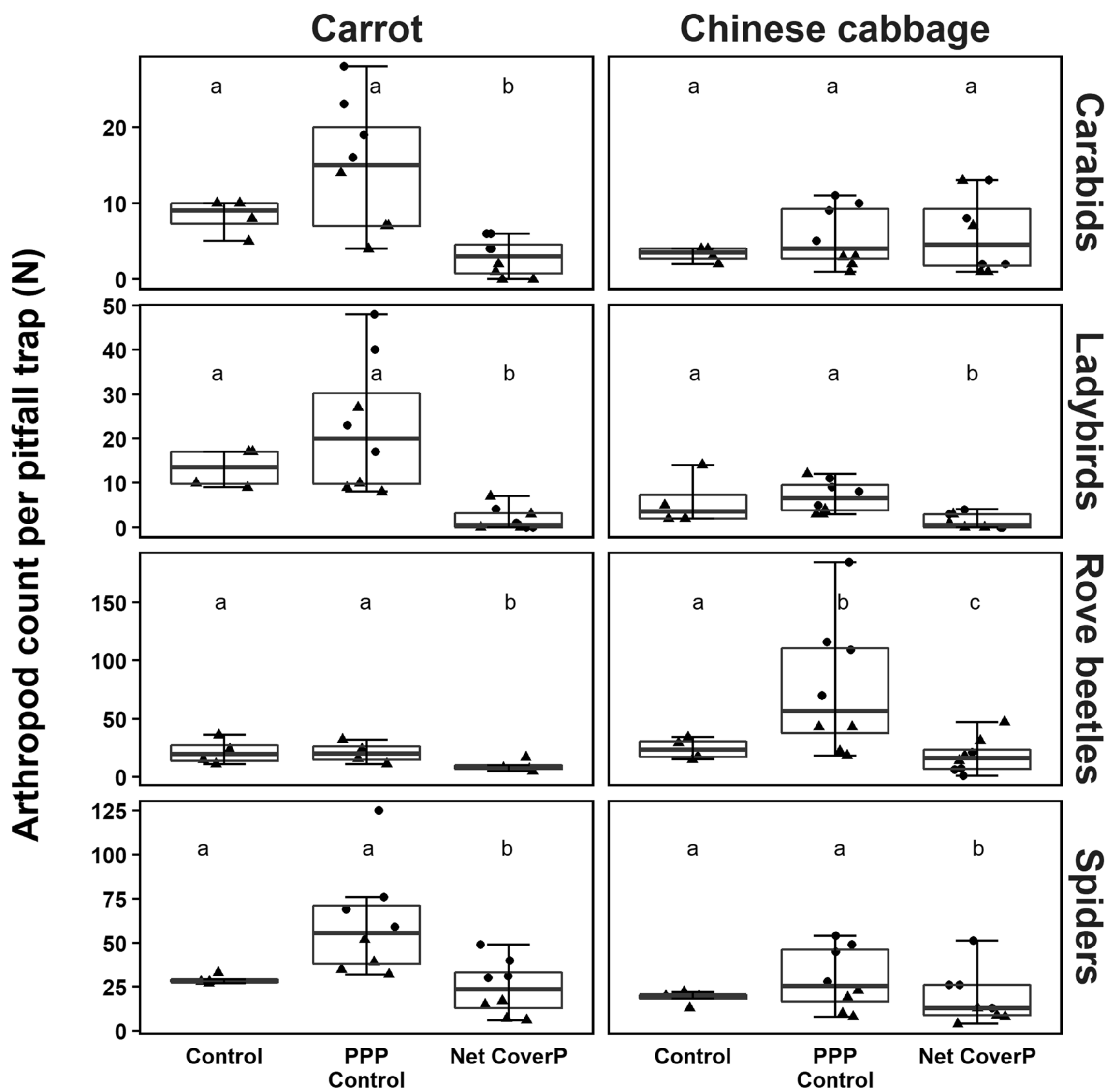

Fig. 10 Natural enemy counts in pitfall trap catches in 2019 and 2020. Points represent replicates. Point shape represents the year (round = 2019, triangle = 2020). Significant differences are indicated by different letters

a net reproductive rate of up to 36 (Ulusoy and Ölmez-Bayhan 2006). Therefore, without natural control, a high population build up is possible in short time. Aphids have several effective natural enemies. These are to date commercially available and applied against similar pests under protected conditions. Ladybirds and syrphids, as important aphid antagonists, were shown to be effectively excluded by net coverage (Dib et al. 2010). Also, in the presented results of the pitfall trap catches in Chinese cabbage and carrot, catches of ladybirds, including larvae, rove beetles, and spiders, were significantly reduced under net cover as compared to uncovered crop (Fig. 10). Ladybirds and spiders play a major role in control of aphids, for instance Fidelis et al. (2018) revealed the most prominent mortality factors of *B. brassicae* in cabbage fields to be Syrphid larvae, Coccinellidae, Aphidoletes larvae and spiders, listed in order of their importance. Ludwig and Meyhöfer (2016) also found a significant reduction in spiders under 0.8 mm meshed net covers on Brussel sprouts, and an increase in *Myzus persicae*. On the other hand, the same study did not detect significant effects on aphid parasitism rate or syrphid larvae abundance. Together with the cited studies, the presented results reveal that the exclusion of ladybirds and spiders plays an important role for population increases in aphids under net coverage in Chinese cabbage crop. Their exclusion will likely also play a major role for the observed aphid increase under net in carrot (Fig. 2).

Also, leaf miners can effectively be controlled by natural enemies. The high efficacy of parasitoids such as *Dacnusa sibirica* and *Dyglyphus isaea* for instance resulted in their

Table 3 Temperature and relative humidity below net cover and in uncovered cultivation

Year	Timespan	Crop	Treatment	Temperature (°C) (mean, min–max)	Relative humidity (%) (mean, min–max)
2019	Jun 6–Sep 25	Carrot	Uncovered	**18.9**, 1.0–43.6	**79.6**, 0.0–100.0
			Net cover	**19.2**, 0.9–47.4	**74.1**, 0.0–100.0
	Jul 11–Aug 1	Chinese cabbage	Uncovered	**21.7**, 9.8–53.3	**78.6**, 0.0–100.0
			Net cover	**21.9**, 9.4–45.6	**77.2**, 20.3–100.0
2020	May 11–May 29, Aug 8–Sep 10	Carrot	Uncovered	**18.8**, − 0.3–47.3	**66.3**, 0.0–100.0
			Net cover	**18.8**, − 0.1–44.1	**72.4**, 0.0–100.0
	Jun 22–Jul 10	Chinese cabbage	Uncovered	**19.3**, 9.4–34.7	**78.9**, 0.0–100.0
			Net cover	**19.8**, 9.4–39.2	**79.4**, 0.0–100.0
	Jul 13–Jul 31	Leek	Uncovered	**20.7**, 7.2–41.0	**72.0**, 0.0–100.0
			Net cover	**19.7**, 5.5–37.5	**67.4**, 0.0–100.0

For uncovered cultivation, climate data of the PPP Control are shown as a reference. Data were recorded continuously during the given timespan with one data logger per replicate (N = 4 per treatment), and data of all loggers were used to calculate the mean, max and min values shown in the table

Table 4 Photosynthetic active radiation (PAR) below net cover and in uncovered cultivation

Days of measurements	Crop	Treatment	PAR (mean, min–max)
2020-08-25	Carrot	Uncovered	**329.2**, 58.9–642.5
2020–09-24		Net cover	**157.8**, 53.3–648.7
2020–07-13	Chinese cabbage	Uncovered	**42.3**, 10.0–100.0
2020–07-14		Net cover	**19.1**, 10.0–100.0
2020–09-02	Leek	Uncovered	**278.1**, 86.4–1035.7
2020–09-17		Net cover	**197.3**, 80.7–698.0

For uncovered cultivation, PAR data of the PPP Control are shown as a reference. Data were recorded continuously between maximum 9 am to 4 pm, replicated at two days with cloudy versus sunny weather, and the full timespan was used to calculate the mean, max and min values shown in the table

commercialization and broad use in greenhouse crop production (Head et al. 2003). Due to a mean lifetime fecundity of about 133 eggs per female during the 40 days oviposition period (Shakeel et al. 2009), invasion of a few adults is enough to produce significant larval damage, if natural control is missing. However, which natural enemies play a major role in open field and if the net cover excludes them, cannot be stated as clearly as for the aphid case based on the current study. However, for adult mining flies, spiders are likely to be relevant mortality factors that were reduced by net coverage (Fig. 10).

Interestingly, other species like flea beetles or cabbage root fly seemingly did not profit in the same way from these effects. In regard to flea beetles, this theoretically could mean that they were fully excluded by the net cover. Some feeding through the net that was observed during the trials could also have caused the measured damage. However, the existence of damage by cabbage root fly larvae in the covered plots clearly indicates that some individuals of this pest were present under the nets. Therefore, it seems more likely that the effect of natural enemies and their exclusion by the netting is of higher importance for the population growth regulation of aphids and mining flies as compared to the other pests. This assumption is reasonable, because in case of flea beetles, only adult damage on Chinese cabbage was monitored, and there is no effective natural enemy known for this beetle (Olson and Knodel 2002). Also, with only 2–3 generations per year and a development time from egg to adult of 32–43 days (Olson and Knodel 2002), the main damage in the eight week crop cycle of Chinese cabbage (Table 2b) is expected due to invading adults, not due to reproduction in the crop. For *D. radicum*, the net cover likely effected the invasion of *Aleochara* spp., as lower catches of rove beetles were observed in the trials (Fig. 10), but soil-borne antagonists of larval stages such as entomopathogenic nematodes (Andreassen et al. 2009; Beck et al. 2014) will not be excluded. And again, an attack of larvae by natural enemies, especially arthropods, after having entered the plant is unlikely.

For caterpillars, there was no strong reduction neither strong increase visible below nets. A combination of the effects of attack hurdles by the nets for Butterflies on the one hand, and the exclusion of natural enemies like birds on the other may have balanced out each other in the trials.

Egg laying through net was observed in the trials, as also described in the literature (Hommes 1993). However, as species were not differentiated in this study, effects may differ on species level.

It can be concluded that net cover can protect pests from their natural enemies, and that the invasion of aboveground predators is strongly reduced by their relatively large body size. Even if their larval stages are the ones that attack pests, they do not occur in relevant numbers below the nets because main dispersal takes place by adults. As visible in the results of 2020 in Chinese cabbage and carrot, the effect of net cover was much stronger as compared to a cautious use of insecticides, which did not show significant changes in natural enemy densities as compared to the insecticide free control plots (Fig. 10). The exclusion of natural enemies by the net cover will have the more impact on pest population development, the more effective the natural enemies control the respective pests, and the higher the reproduction rates of the pests. The often observed effective control of aphids by natural enemies under field conditions underlines the findings of the current study. In addition, the successful control of aphids with natural enemy introductions in greenhouse production supports the assumption that natural enemy exclusion plays a major role here. These arguments and the results for aphids have many similarities to the case of leafminers, but evidence is lower because no monitoring of relevant natural enemies was carried out in this study.

For thrips protection, coverage with the 0.35 mm meshed net showed good efficacy in leek trials in 2019 and 2020 (Fig. 7, Fig. 8). Thrips live very hidden, especially in Allium crop such as leek, and the possibility to control them in such crop by natural enemies is limited (Theunissen and Legutowska 1991; Tatemoto and Shimoda 2008). Furthermore, in this trial, the net was removed fewer times (Table 2) and much shorter, just to carry out the weed control and fertilization. However, a later check revealed that thrips, in this case *Frankliniella occidentalis* from an internal rearing, were able to pass through the tested Net0.35. They easily escaped from a small box covered by the respective netting (unpublished data). Consequently, the net used in the trials was not suitable to ensure exclusion of thrips physically. Because a clear reduction in damage and thrips counts under the net could be measured in spite of this finding, other effects must have played a role here. Such effects could be a visual coverage of the crop. The net coverage was white, and white has been shown to be less attractive to *T. tabaci* as compared to yellow or blue color (Pobozniak et al. 2020). Because thrips will test the potential host surface for its suitability for feeding (Riefler and Koschier 2009), unsuccessful probing on the net could also have led to redirection of the arriving thrips. Visual coverage and/or unsuccessful probing could also explain the results of 2019. Here, the control was covered with the Net0.8, but this net cover did not show the good reduction in thrips damages as compared to the Net0.35 in the same trial (Fig. 7). In accordance with this, a direct flight through the fine mesh is more unlikely as compared to the coarser Net0.8. Thrips counts in 2020 show that the reducing effect of net coverage vanishes in the later season as compared to the PPP Control (Fig. 8). This can be explained by the timing of the weekly PPP applications in the PPP Control, with 0, 4 and 7 applications carried out before thrips counts at Aug 4, Sept 1 and Sept 21, respectively (Table 2c). In any case, the thrips reduction using the net coverage was still comparable to the PPP control after 7 PPP applications. Also the good fixation of the net to the ground and the short opening times of nets seem of high importance here. This is concluded from usability tests of the Net0.35 in 2021 at commercial growers, where the positive effects shown in this paper could not be reproduced (unpublished data). The main difference was that growers installed and managed the net coverage in an economical manner. This means, in order to make management efficient, larger distances between sandbags fixing the net boarders to the ground were chosen. In addition, longer opening times at growers' fields can be expected. Both effects likely limited the performance of the net cover.

In addition, some impact of the net covered treatments on plant disease development was observed. One was a significant increase in *Puccinia* spp. in leek under net coverage in 2020 (Fig. 6B). However, there was also a significant increase in *Puccinia* spp. infestation in the PPP Control in 2019 as compared to both net covered treatments (Fig. 6A). The regular spraying with handheld sprayers in the PPP Control as well as the coverage and removing procedures of the net may have caused small cracks in outer leaves that may have functioned as entrance for the infection. For carrots, the leaf area covered with black spots assigned to *Alternaria* spp. infection on carrot leaves was higher under net coverage (Fig. 1), but there were no symptoms on roots. Also here, damages by the net coverage on leaves may have favored infestation. In spite of the very similar infestation rates in 2020, wet rot in Chinese cabbage on the other hand was overall increased in the PPP Control. The significance of the result can be explained by the higher number of plants sampled per replicate in 2019 (15 versus 5 in 2020). However, because the untreated Control was not significantly different to the net covered treatments, differences should not be interpreted as a difference between covered and uncovered treatments in general. The effect was mainly due to an increase in 2019 in the PPP Control, and because there were many more insecticide treatments that year as compared to 2020 (Table 2b), the increased spreading of infections was likely caused by more frequent presence of workers in these plots. This argumentation in regard to plant pathogens is supported by the fact that many plant pathogens are only able to infect plants through wounds, although for instance *Puccinia* spp. can also easily infest via intact plant surfaces

(Schlösser 1997). Nevertheless, also other factors that were not analyzed in this study could have supported infestations. For instance, a slower drying of leaf surfaces under net coverage and favorable wind conditions could have supported development of plant diseases.

Net coverage did additionally have some measureable impacts on the microclimate, but the effect was very limited at least regarding the mean RH and temperature measurements (Table 3). A relatively strong reduction in radiation of 30–50% was detected (Table 4). Nevertheless, net coverage resulted in a significant higher yield in cabbage and leek when harvest was carried out at the same time with uncovered plots (Fig. 5, Fig. 9B). For carrots, no difference in yield could be detected (Fig. 3). Weighting of only one mixed sample per replicate may have concealed minor yield differences in this crop. It cannot be concluded clearly from this study, why netting had positive effects on yield in some crop. In leek for instance, pest and disease levels were too low to explain differences. It could be the case that the presumably reduced wind speed under the net is a positive factor, but this was not measured. It should also be mentioned that analyses regarding the PAR were additionally carried out by project partners at another location, and reductions were much lower in comparison with the presented measures (unpublished data). The concrete location of the sensors may have played a role here and more measurements will be needed to clarify the effect on PAR.

To conclude, it is assumed that net coverage with mesh size 0,8 mm is an adequate control tool for some major pests in Chinese cabbage, but at the same time excludes many natural enemies from the covered areas. The data suggest that growers should monitor the flight of aphids and mining flies in order to carry out net removals outside flight periods of the respective pests if possible. In carrots, no positive effects of net coverage were observed in this study. Depending on handling, net coverage against thrips in leek could also become an effective measure, and the crop is suitable for net coverage. Some increase in diseases can be expected but appears acceptable in Chinese cabbage and leek taking into account the measured reductions of relevant pests and increases in yield.

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Declarations

Competing interest The author has no competing interests to declare that are relevant to the content of this article.

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