Cyclamen mite (Acari: Tarsonemidae) monitoring in eastern Canada strawberry (Rosaceae) fields and its potential control by the predatory mite *Neoseiulus cucumeris* (Acari: Phytoseiidae)

Stéphanie Patenaude[a], Stéphanie Tellier[b], and Valérie Fournier[a]*

[a]*Centre de recherche et innovation sur les végétaux (CRIV), Département de phytologie, Université Laval, 2480 Boulevard. Hochelaga, Ville de Québec, Québec, G1V 0A6, Canada;* [b]*Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, Direction régionale de la Capitale-Nationale, 1685 boulevard Wilfrid-Hamel, local 140, Ville de Québec, Québec, G1N 3Y7, Canada.*

*corresponding author:

Phone: (418) 656-2131 ext. 404629

Email: valerie.fournier@fsaa.ulaval.ca

Address: Centre de recherche et innovation sur les végétaux,
Département de phytologie, Université Laval,
2480, boul. Hochelaga, Québec, Qc, G1V 0A6

Abstract—The cyclamen mite (*Phytonemus pallidus* Banks; Acari: Tarsonemidae) has recently become a more important pest in Canadian strawberry (*Fragaria* × *ananassa* Duchesne ex Rozier; Rosaceae) production with the withdrawal of the pesticide endosulfan in 2016, yet its phenology under field conditions in Canada is poorly known. Moreover, while its biological control with predatory mites has shown potential, the effectiveness of this method has never been investigated under eastern Canadian field conditions. The objectives of this study were to 1) monitor populations of *P. pallidus* in strawberries for two consecutive years; and 2) evaluate the in-field potential of the predatory mite *Neoseiulus cucumeris* Oudemans (Acari: Phytoseiidae). Monitoring cyclamen mite populations in the field revealed new critical knowledge about its phenology in eastern Canada, such as activity until late November. The predator *N. cucumeris* was able to effectively suppress cyclamen mites the first year, but appeared to be too cold-sensitive to maintain adequate control toward the end of the season. Furthermore, the high rates of predator release required would most likely be cost prohibitive for commercial use. Control of the cyclamen mite in strawberries remains a complex issue that will require further research.

Introduction

Pest and disease issues represent constant challenges for strawberry (*Fragaria* × *ananassa* Duchesne ex Rozier; Rosaceae) producers. Among these, the cyclamen mite (*Phytonemus pallidus* Banks; Acari: Tarsonemidae) has been an increasing source of concern around the world in recent years (Fig. 1A). This major pest, sometimes known as the strawberry mite, is a phytophagous mite that feeds on young leaves before migrating to the flowers and fruits later in the season (Schaefers 1963). Infested leaves become distorted, wrinkled, and stunted (Fig. 1C). Under severe infestation, plants become dwarfed with brown, brittle leaves (Alford 2007). Fruits first turn brown under the sepals, then remain small and dry as infestation progresses (Jeppson *et al*. 1975; Hoy 2011), which leads to widespread fruit rejection and yield reduction (Fig. 1D).

Control of cyclamen mites is very difficult and rather complex. Because they are not easily visible, early detection is arduous, and they are often discovered only when symptoms appear. Cyclamen mites live inside young folded leaves and flower buds, which shield them from most control methods, including non-systemic acaricides (Zhang 2003; Fitzgerald *et al*. 2008; Hoy 2011). This species is mainly parthenogenetic, and females can lay an average of two eggs per day for a mean oviposition period of eight days (Easterbrook *et al*. 2003; Alford 2007; Rostami *et al*. 2018). In addition, several generations overlap during the season, and adult females overwinter on site, deep in the crown of the plant (Jeppson *et al*. 1975; Alford 2007). Consequently, infestations can become very problematic in multi-year strawberry production systems such as the matted row system, common in the province of Québec, Canada. Historically, producers have achieved effective control of this pest with endosulfan sprays (Schaefers 1963; Stenseth and Nordby 1976; Łabanowska 1992). However, this acaricide has been withdrawn in many countries in recent years, due to its deleterious effects on the environment and human health. It is also banned in Canada as of 31 December 2016 (Gouvernement du Canada 2011). Since then, much research has aimed to identify other effective acaricides, but results among studies are variable and the acaricides studied only appear to provide partial control of this pest (Raudonis 2006; Gobin and Bangels 2008; Zalom *et al*. 2009; Fountain *et al*. 2010; Lafontaine *et al*. 2011; Łabanowska *et al*. 2015). Therefore, finding an alternative to chemical control is essential.

Biological control with predatory mites (Acari: Phytoseiidae) is a promising solution (Fig. 1B). In the last 20 years, many indigenous and introduced species have been studied as biological control agents against the cyclamen mite. The phytoseiid mite *Neoseiulus cucumeris* Oudemans (Acari: Phytoseiidae) is one of the predators most recommended against *P. pallidus* by biological control supply companies, and the most studied. Indeed, its effectiveness against this pest has been known for more than 60 years (Huffaker and Kennett 1953), and, despite great variability, has been demonstrated in many studies (Croft *et al*. 1998; Easterbrook *et al*. 2001; Berglund *et al*. 2007; Petrova *et al*. 2008; Svensson 2008; Tuovinen and Lindqvist 2010). However, as *N. cucumeris* is known to be sensitive to cold temperatures (Gillespie and Ramey 1988; Jones *et al*. 2005; Svensson 2008) and most studies originate from countries where this predatory mite often overwinters, its efficacy and survival under the Canadian climate remain unknown.

Previous experiments on the biological control of *P. pallidus* have mostly been performed under laboratory conditions or in protected crop production systems, such as greenhouses, and no field study has been performed in a commercial context in the temperate climate of Canada. Furthermore, studies on population dynamics of *P. pallidus* are scarce and were mostly performed under controlled conditions (Schaefers 1963; Jeppson *et al*. 1975; Easterbrook *et al*. 2003; Rostami *et al*. 2018). Although they provide a good basis, they do not reflect the specific complexities of dynamics in the field. Thus, the objectives of this study was to monitor cyclamen mite population dynamics in the field for two consecutive years to better understand its phenology and evaluate the effectiveness of the predatory mite *N. cucumeris* to control *P. pallidus* under commercial strawberry field conditions.

Materials and methods

Both the phenology and the in-field biological control experiments were conducted on a commercial strawberry farm located in Sainte Foy (46°46'6.7"N, 71°23'56.5"W), Québec, Canada. They were performed in a June-bearing strawberry (cultivar Jewel) field planted in matted rows in the spring of 2015. In 2015, the plantation was in an establishment phase where daughter plants (runners) were allowed to establish in bare land to form a dense and intertwining bed. In 2016 and 2017, the field was in production. After each production year, the plantation has been renewed (renovation) by mowing the foliage to maintain the productivity of the plants. A straw mulch was also applied on the plants in late fall to protect them from frost injury, then removed the next spring. At the end of the 2017 production season, the field has been tilled by growers following the usual management of the matted row system.

Phenology of the cyclamen mite

Field set up. To better understand *P. pallidus* in the field, three untreated plots were monitored in 2016 and 2017 on the strawberry farm in Sainte Foy. The field was renewed by mowing on 2 August 2016, and tilled on 10 July 2017, according to the usual crop management practices of the producer. Plots consisted of three rows (12 m^2) of strawberry plants. Two HOBO data loggers (Onset, Bourne, Massachusetts, United States of America) were placed in the field to record temperature and humidity at the canopy level.

Sampling. Ten young folded trifoliate leaves were randomly sampled once a week from 14 June 14 to 29 November 2016, and from the date of straw mulch removal (May 4) until the tilling of the field at the end of the harvest (July 10) in 2017. Leaves were placed individually in plastic bags and immediately stored in a cooler. In the laboratory, samples were kept at 4 °C until counting. Both sides of leaflets were examined under a stereomicroscope, and held wide open in order to clearly see *P. pallidus* on leaf veins and in creases. For this descriptive analysis, the number of eggs, larvae, females, and males of *P. pallidus* were counted visually.

In-field biological control

Experimental set up and treatments. Three treatments were compared: (1) introductions of *N. cucumeris*; (2) acaricide (abamectin, Agri-Mek SC , Syngenta Crop Protection Canada, Guelph, Ontario, Canada) applications, and (3) untreated control. Treatments were replicated six times in a randomised complete block design, for a total of 18 plots. The experimental unit was a 12 m^2 plot, consisting of three rows of strawberry plants in the first year of production. To prevent plot contamination, a 20-m buffer zone was established on the perimeter of each plot. Temperature and humidity were recorded using a HOBO data logger placed at canopy level in two plots. The field was managed by the producer according to their usual practices. If insecticide treatment had to be applied in the field (for example: against *Lygus lineolaris* (Palisot de Beauvois); Hemiptera: Miridae), all plots were covered with a waterproof plastic tarpaulin during spraying to prevent potential deleterious effects on phytoseiid mites.

Predator releases. Curative release rates of *N. cucumeris* (Koppert Biological Systems, Berkel en Rodenrijs, The Netherlands) were based on the recommendations of the biological control supplier. Introduction frequency and rates were adjusted as necessary, according to weekly counts. Thus, predators were introduced every one or two weeks from 21 June 21 to 10 August 2016. In total, two releases of 500 *N. cucumeris* m^{-2} and four of 1000 *N. cucumeris* m^{-2} were carried out. Numbers of predators required per plot to achieve high curative rates were obtained by measuring the volume of the vermiculite mixture from the commercial containers. Because of the large quantities needed, the numbers of predators were estimates, rather than based on actual individual counts (Rhodes *et al*. 2006). Therefore, the volume of mixture per release was 124 mL or 248 mL (500 or 1000 *N. cucumeris* m^{-2}) per plot. The viability of predatory mites was assessed prior to each release, by observing three representative samples of the bottle (after a gently rotation) under a stereomicroscope for at least 10 minutes. Predatory mites were released in the field in the late afternoon for optimal conditions, within 24 hours after delivery by the supplier. The measured volume of the vermiculite mixture containing predatory mites was sprinkled on the foliage evenly within the plots.

Acaricide application. The acaricide treatment consisted of abamectin (Agri-Mek SC), sprayed after foliage mowing (2 August 2016) during post-harvest operations.

This compound was selected because of its previously documented efficacy against *P. pallidus* and common use among Québec producers. Since abamectin has no effect on eggs (Labanowska *et al.* 2015), two applications were performed, on 9 August and 22 August 2016, at a rate of 225 mL of Agri-Mek SC/ha with the addition of 0.2 % non-ionic adjuvant Agral (Syngenta Crop Protection Canada). Total spray volume (2000 L/ha) was applied by producers using a conventional mounted field sprayer equipped with a number 8010 spray nozzle regulated at a pressure of 413.7 kpa.

Sampling. A total of 10 young folded leaves per plot were randomly sampled every week from 21 June 21 to 6 September 2016 and then every two weeks until 17 October. Leaves were stored and counted in the laboratory following the method described in the phenology section of the Materials and methods. Motile stages (female, male, larvae) and eggs of *P. pallidus* and phytoseiid mites were counted. Phytoseiid mites were collected with a fine brush and kept in a 70% ethanol solution until mounted on a microscope slide in polyvinyl alcohol mounting medium (BioQuip Products, Rancho Dominguez, California, United States of America) for taxonomic identification by the Laboratoire d'expertise et de diagnostic en phytoprotection (Quebec Ministry of Agriculture, Ville de Québec, Québec, Canada). When necessary, identification of phytoseiid specimens was validated by Dr. Frederic Beaulieu, acarologist at the Agriculture and Agri-Food Canada National Identification Service (Ottawa, Ontario, Canada). Not all phytoseiid mites counted could be identified, either because they could not be captured during the count, were too damaged to be mounted on a slide, or were impossible to identify (*e.g.*, characteristic features not visible). Voucher specimens were deposited at both the Laboratoire d’expertise et de diagnostic en phytoprotection du MAPAQ in Québec City.

Second-year follow-up observations. In the fall of 2016, the plantations of half of the plots were destroyed by the producer due to plant disease. However, to observe change in treatments over time, the nine remaining plots (three repetitions of each treatment) were sampled weekly until 29 November 2016, and then from 4 May to 10 July 2017, using the method described above. As the aim of the follow-up observations was to monitor the treatment effect over time, no acaricide or predatory mite treatments were carried out in these plots in 2017.

Fruit yield could not be measured in 2016 but was assessed in 2017 on the nine remaining plots. Harvest area consisted of a 1-m^2 subplot within each plot. Strawberries were harvested twice a week from 26 June to 10 July 2017. Fruits were classified as marketable or unmarketable. Unmarketable fruits were either smaller than 6 g or damaged by disease, pests or abiotic factors. Fruits in each category were subsequently counted and weighed.

Statistical analysis. No statistical analyses were performed for the phenology of the cyclamen mite, as this part of the study was purely descriptive. For the part on biological control, we evaluated the treatment effect using two-way analysis of variance with repeated measures and fitted to the data using the MIXED procedure of SAS (SAS Institute, Cary, North Carolina, United States of America). In each model, the correlation structure that best fit the data was chosen based on the Akaike information criterion. Numbers of *P. pallidus* were square-root transformed to meet the normality assumptions, except for the 2016 experiment, for which the log-transformation was used. No statistical *t* analysis could be performed on predatory mites due to the high proportion of zeros, despite trying with glmmADMB and Binomial model (glimmix) for zero-inflated data of R Software (R Development Core Team 2013). Fruit yields (2017) were analysed with the same analysis of variance model, but on the raw data. Following a significant effect in any of the analysis of variance tables, the protected least significant difference method was used to identify pairs of treatments that showed differences. All analyses were performed at a significance level of 5% and all the least square means were reported on the scale of the raw data.

Results

Phenology of the cyclamen mite

In 2016, sampling began on 14 June when strawberry plants were blooming. At that time, only very few *P. pallidus* were observed (Fig. 2). Over the following weeks, the population increased continually and peaked at the end of August, then started to decrease for all stages, especially the number of eggs. Field sampling stopped on 29 November, as strawberry plants were covered with ice and snow. However, active *P. pallidus* individuals (females and immatures) were still counted on this date.

In 2017, sampling began when the straw mulch was removed. From then until 29 May, few *P. pallidus* were detected, although high population levels had been documented in these plots during the previous season. At the beginning of June, the population increased rapidly then stayed relatively constant until the end of the observations. The overall population increased about a month earlier in 2017 compared to 2016. The female:male ratio was very high, with a two-year average of 93% females for 7% of males, ± 5%.

In-field biological control

A total of six predator introductions were carried out from 21 June to 10 August (Fig. 3A). At the beginning of the season, *i.e.*, from mid-June to mid-July, *N. cucumeris* failed to cause a decrease in the *P. pallidus* populations despite two releases (Fig. 3A). Abnormally cold nights (2.4 °C on 24 June 2016) at the end of June might have affected survival and efficacy of the first batch of predators introduced (Supplementary Fig. 1). The effects of this sensitivity to cold may have persisted for some time, as the phytoseiid population was still very low at the end of July, despite a third release. Thus, as of 19 July, introduction rates were doubled, and carried out weekly instead of every other week. Afterwards, the number of cyclamen mites decreased in the *N. cucumeris* treatment and these plots became distinct from the control plots. The interaction treatment X period (sampling dates) was significant ($F_{28,210} = 5.34$, $P < 0.001$) for *P. pallidus* motile forms (Fig. 3A). Following the first acaricide application on 9 August, the cyclamen mite densities in the acaricide and *N. cucumeris* treatment plots were comparable for two weeks, but different from the control ($F_{2,210} = 21.56$, $P < 0.001$; Fig. 3A). Following the second acaricide application on 22 August, the *P. pallidus* densities in the acaricide treatment became significantly different from those in the two others treatments ($F_{2,210}$ = 14.67, $P < 0.001$) and this difference remained until the end of the experiment. At the end of the season, the number of motile forms began to decrease in the control treatment while those in the *N. cucumeris* treatment increased. Consequently, these two treatments did not differ.

The early season phytoseiid mite densities were low in the *N. cucumeris* treatment (Fig. 3B), even though predatory mites had already been released twice in these plots. The number of phytoseiid mites started to increase as of 26 July, but the density decreased rapidly as of 22 August until the end of the season. Few phytoseiid mites were found in other treatments during the experiment, and consisted mainly of naturally occurring *N. fallacis*. After the first acaricide, no phytoseiid mite was found in this treatment until 3 October.

Second-year follow-up observations

To evaluate the residual effects of *N. cucumeris* the following year, nine plots were monitored in spring and summer 2017 (Fig. 3C). The interaction treatment X date was significant for the two years combined ($F_{58,174}$ = 4.72, $P <$ 0.001).

In the spring of 2017, the number of *P. pallidus* motile forms was low, and remained similar among treatments until 29 May. A week later, populations increased rapidly for all treatments. Between 20–26 June 2017, the number of *P. pallidus* exploded in the *N. cucumeris* treatment and even surpassed the control, becoming significantly different on 10 July ($F_{2,174}$ = 22.92, $P < 0.001$). Density in the acaricide treatment remained low from 15 August 2016 to 10 July 2017. On the last sampling date (10 July 2017), the acaricide treatment had the lowest number of motile forms per leaf, followed by the control and finally by *N. cucumeris*. No phytoseiid mites were found in the 2017 samplings (Fig. 3D).

Fruit yield

Fruit yield was measured only for the second year of the study (2017). Marketable yield was significantly different for all treatments ($F_{2,4} = 22.05$, $P = 0.007$) and decreased in the following order: acaricide, *N. cucumeris,* and control (Fig. 4). The acaricide and *N. cucumeris* treatments produced similar total yields ($t_4 = 1.8$, $P = 0.150$), which were higher than that of the control ($F_{2,4} = 12.12$, $P = 0.020$). Fruit size also differed among treatments (marketable: $F_{2,4} = 9.94$, $P = 0.028$; unmarketable: $F_{2,4} = 19.16$, $P = 0.009$). The average fruit weight for marketable strawberries was higher for the acaricide treatment than the control, whereas the *N. cucumeris* treatment was intermediate and not different from the two others.

Discussion

This study represents the first report of cyclamen mite control by *N. cucumeris* in strawberry fields in eastern Canada. Our results highlight some of the challenges of using biocontrol agents under field conditions in northern countries. Indeed, despite its effectiveness against *P. pallidus*, some factors complicate the timing of *N. cucumeris* introductions and impact its performance in the field, thus compromising the potential for its use in a commercial context.

Phenology of *Phytonemus pallidus* in the field

We found, unlike any previous study, actively feeding mites until the end of November. This could represent a greater management challenge, for example, during a mild fall or under the microclimate of a floating row cover, a sheet of fabric laid over plants to extend the growing season or protect the plantation from frost. However, additional monitoring of strawberry fields located in various parts of Canada is needed to confirm whether this late occurrence is common or purely anecdotal.

Field monitoring of *P. pallidus* also allowed us to draw attention to the extent of the challenges of its detection early in the growing season. Although high densities of *P. pallidus* were present in the fall 2016, only small numbers were detected the following spring. However, the population outbreak that occurred within a week at the beginning of June 2017 suggests that reproduction started in the crown of the plant long before being detectable on young leaves. According to Jeppson *et al*. (1975), females start laying eggs in mid-April in Canada. However, their migration from the crown seems to be gradual and unpredictable. Destructive sampling of the crown would be advisable in future research to better understand the early season behaviour of *P. pallidus* that complicates early detection and estimation in the field. As a result, determining the necessity of treatment and optimal timing represent quite a challenge for producers and agronomists. Moreover, when hidden in the crown, *P. pallidus* are, practically speaking, impossible for predators to reach. This characteristic is known to be a factor limiting the effectiveness of augmentative biocontrol (Collier and Van Steenwyk 2004).

To our knowledge, the first and only study to document *P. pallidus* population dynamics in first-year production strawberry fields was conducted by Schaefers (1963) in New York State, United States of America. However, comparisons are difficult, as observations were only performed once in that study. It is possible that another timing or pattern would occur under different temperature and humidity conditions (*e.g.*, warmer fall). Lastly, our observations confirmed some well-known characteristics of *P. pallidus*, such as its high rate of reproduction and the large proportion of females, the two-year average of 93% females being similar to the 95% reported in the literature (Alford 2007).

***Neoseiulus cucumeris* efficacy in the field**

Previous studies in Europe and United States of America found that *N. cucumeris* could provide satisfactory control of *P. pallidus* with a single introduction (Croft *et al*. 1998; Petrova *et al*. 2000; Easterbrook *et al*. 2001; Tuovinen *et al*. 2009)), but our study did not entirely corroborate these findings. *Neoseiulus cucumeris* did offer adequate control of *P. pallidus* in August, but was less effective at the beginning and at the end of the season.

The high sensitivity of *N. cucumeris* to cold temperatures may explain the poor performance of the predators at these times of the year. The few cold nights with temperatures near the freezing point after the first introduction in June could have affected their survival, as Gillespie and Ramey (1988) showed that only 1.2% of non-acclimated *N. cucumeris* survive at 2 °C. Thus, a sudden drop in temperature, such as a sub-zero night just after the introduction, may not leave them enough time to achieve cold hardening.

In addition, the short growing season and overall cold climate of the Ville de Québec area may not be suitable for *N. cucumeris*, resulting in sub-optimal performance against *P. pallidus* in early and late season. Temperature is one of the most important factors impacting phytoseiid mite reproduction and development (Ghazy *et al*. 2016). Indeed, a rise in temperature from 20–25 °C has led to better predation and oviposition rates of *N. cucumeris,* resulting in more effective control of Thysanoptera (Jones *et al*. 2005). Unfortunately, temperatures above 25 °C rarely occur in the summer, and mainly in July-August, in the Ville de Quebec area. The weather might also affect *P. pallidus* and predatory mite development differently, resulting in a divergence in population size between the two species. Indeed, unfavourable environmental conditions during releases and inappropriate timing have been found to be among the most common ecological limits on augmentative biocontrol (Collier and Van Steenwyk 2004). A temporary lack of pollen in the field is another potential explanation for the lack of *N. cucumeris* activity early in the season. Indeed, Tuovinen and Lindqvist (2010) showed that *N. cucumeris* maintained good preventive control of *P. pallidus* but the number of predators dropped drastically a week after the end of the cattail pollen supply, although cyclamen mites were present.

No residual effects of the *N. cucumeris* treatment were noted after the overwintering period. *Phytonemus pallidus* density in the *N. cucumeris* treatment even surpassed the control treatment in June 2017. The absence of *N. cucumeris* in

2017 may be part of the explanation, as this predatory mite is not known to overwinter in Nordic countries (Svensson 2008). Accordingly, no predatory mite was found during sampling in 2017 (Fig. 3D). This difference can also be explained by the fact that strawberry plants in the control treatment were severely damaged by *P. pallidus* in the fall of 2016. Thus, poor plant regrowth in 2017 led to rapid deterioration of the leaves, which could no longer support high *P. pallidus* density; this in turn resulted in high natural mite mortality (Schaefers 1963). In contrast, plants in the *N. cucumeris* treatment showed normal growth in the fall. Consequently, more leaves were available to support cyclamen mite growth in 2017.

Despite the absence of *N. cucumeris* in 2017, a treatment effect on fruit yield was detected in the second year following treatment. The *N. cucumeris* treatment provided 48% more marketable yield than the control plots. It is possible that a higher marketable yield could have been obtained if *N. cucumeris* introductions had also been performed in 2017. Indeed, Svensson (2008) reported 88% more first-class fruits when treating severe infestation with *N. cucumeris* for two consecutive years. On this farm, yield loss was mainly caused by a decrease in fruit size and number, rather than direct aesthetic damage. Thus, a greater proportion of the yield loss might have been caused by pre-harvest damage, as Stenseth and Nordby (1976) suggested that the reduction in fruit size resulted from a direct attack on flowers and pre-harvest weakening of plants by *P. pallidus*. However, these results must be interpreted cautiously since there were only three replications in 2017, and yield for 2016 was not available for comparison.

Our results point out the many challenges of in-field biocontrol. In addition to temperature, many other environmental stresses, such as humidity or ultraviolet radiation, can impact phytoseiid mite performance, and interaction can also occur between these stressors (Ghazy *et al*. 2016). Contrary to greenhouses, fields are in a fluctuating environment and each year has its unique and unpredictable combination of temperature, humidity, and precipitation. Therefore, the efficacy of in-field biocontrol is difficult to predict. Moreover, early introduction, a key factor in *P. pallidus* biocontrol (Easterbrook *et al*. 2001; Svensson 2008; Tuovinen *et al*. 2009), proves to be a challenge in regions under temperate climate such as Québec. Past studies have pointed out that introduction rates and frequency should be temperature-adapted to maintain the same level of efficacy (Jones *et al*. 2005; Svensson 2008), but this strategy can become expensive and uneconomical for producers. Indeed, the high-rate, repetitive introductions that are required to obtain this level of control in our project turned out to be very expensive (over CAD$5000 per ha). Unfortunately, the indirect benefits of biocontrol, such as a reduced impact on the environment and human health, are rarely taken into account by growers to compensate for the higher costs (Collier and Van Steenwyk 2004).

Acknowledgements

We would like to thank our collaborators for their time and expertise: Thierry Chouffot, François Demers, Caroline Martineau, Olivier Samson-Robert, and Jacinthe Tremblay, as well as grower Laurent Fiset, for providing land and showing strong interest for the entire duration of the project. We are also very grateful to Mario Fréchette and Frédéric Beaulieu for their expertise in taxonomy; Gaétan Daigle and Awa Diop for their statistical assistance; Éric Lucas, Roselyne Labbé, and other anonymous readers for their constructive comments on previous versions of the manuscript; and Aurélie Boilard, Audrey Boivin, Catherine Bolduc, Clémence Landreau, and all members of the Fournier laboratory for their technical assistance. Finally, we are grateful to Koppert Canada for providing predatory mites free of charge.

This work was supported by Programme Prime-Vert (volet 4) en appui à la Stratégie Phytosanitaire québécoise en agriculture du Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec by grant ULAV-1-15-1746 to V.F. and a Natural Sciences and Engineering Research Council of Canada scholarship to S.P.

References

Alford, D. 2007. Pests of fruit crops. A color handbook. Manson Publishing, London, United Kingdom.

Berglund, R., Svensson, B., and Nilsson, C. 2007. Evaluation of methods to control *Phytonemus pallidus* and *Anthonomus rubi* in organic strawberry production. Journal of Applied Entomology, **131**: 573–578.

Collier, T. and Van Steenwyk, R. 2004. A critical evaluation of augmentative biological control. Biological Control, **31**: 245–256.

Croft, B.A., Pratt, P.D., Koskela, G., and Kaufman, D. 1998. Predation, reproduction, and impact of phytoseiid mites (Acari: Phytoseiidae) on cyclamen mite (Acari: Tarsonemidae) on strawberry. Journal of Economic Entomology, **91**: 1307–1314.

Easterbrook, M., Fitzgerald, J., Pinch, C., Tooley, J., and Xu, X.M. 2003. Development times and fecundity of three important arthropod pests of strawberry in the United Kingdom. Annals of Applied Biology, **143**: 325–331.

Easterbrook, M., Fitzgerald, J., and Solomon, M. 2001. Biological control of strawberry tarsonemid mite *Phytonemus pallidus* and two-spotted spider mite *Tetranychus urticae* on strawberry in the UK using species of *Neoseiulus* (*Amblyseius*) (Acari: Phytoseiidae). Experimental & Applied Acarology, **25**: 25–36.

Fitzgerald, J., Xu, X., Pepper, N., Easterbrook, M., and Solomon, M. 2008. The spatial and temporal distribution of predatory and phytophagous mites in field-grown strawberry in the UK. Experimental and Applied Acarology, **44**: 293–306.

Fountain, M.T., Harris, A.L., and Cross, J.V. 2010. The use of surfactants to enhance acaricide control of *Phytonemus pallidus* (Acari: Tarsonemidae) in strawberry. Crop Protection, **29**: 1286–1292.

Ghazy NA, Osakabe M, Negm MW, Schausberger P, Gotoh T, Amano H. 2016. Phytoseiid mites under environmental stress. Biological Control, **96**: 120-134.

Gillespie, D.R. and Ramey, C.A. 1988. Life history and cold storage of *Amblyseius cucumeris* (Acarina: Phytoseiidae). Journal of the Entomological Society of British Columbia, **85**: 71–76.

Gobin, B. and Bangels, E. 2008. Field control of strawberry mite *Phytonemus pallidus*. International Organization for Biological and Integrated Control/West Palearctic Regional Section Bulletin, **39**: 97–100.

Gouvernement du Canada. 2011. Note de réévaluation REV2011-01, Abandon de l'endusulfan. *In* Agence de réglementation de la lutte antiparasitaire SC. *Edited by* Publications Agence de réglementation de la lutte antiparasitaire, Santé Canada. Ottawa, Ontario, Canada.

Hoy, M.A. 2011. Agricultural acarology introduction to integrated mite management. CRC Press, Boca Raton, Florida, United States of America.

Huffaker, C. and Kennett, C. 1953. Developments toward biological control of cyclamen mite on strawberries in California. Journal of Economic Entomology, **46**: 802-812.

Jeppson, L.R., Keifer, H.H., and Baker, E.W. 1975. Mites injurious to economic plants. University of California Press, Oakland, California, United States of America.

Jones, T., Shipp, J., Scott-Dupree, C., and Harris, C. 2005. Influence of greenhouse microclimate on *Neoseiulus* (*Ambyseius*) *cucumeris* (Acari: Phytoseiidae) predation on *Frankliniella occidentalis* (Thysanoptera: Thripdae) and oviposition on greenhouse cucumber. Journal of the Entomological Society of Ontario, **136**: 71–83.

Labanowska, B.H. 1992. Effectiveness of acaricides in the control of strawberry mite (*Phytonemus pallidus* ssp. fragariae Zimm.). Fruit Science Reports, **19**: 137–146.

Labanowska, B.H., Piotrowski, W., Korzeniowski, M., and Cuthbertson, A.G.S. 2015. Control of the strawberry mite, *Phytonemus pallidus* (Banks) in strawberry plantations by alternative acaricides. Crop Protection, **78**: 5–14.

Lafontaine, P., Tremblay, J., Bouchard, A., and Martinez, S. 2011. Évaluation de l'efficacité de nouveaux acaricides contre le tarsonème du fraisier (*Phytonemus pallidus* (Banks)) et de leur impact sur les ennemis naturels. Rapport final réalisé dans le cadre du Programme de soutien à l'innovation horticole (PSIH) du MAPAQ, projet PSIH 09-2-122. Carrefour industriel et expérimental de Lanaudière, L'Assomption, Québec, Canada.

Petrova, V., Cudare, Z., and Steinite, I. 2000. The efficiency of the predatory mite *Amblyseius cucumeris* (Acari: Phytoseiidae) as a control agent of the strawberry mite *Phytonemus pallidus* (Acari: Tarsonemidae) on field strawberry. Acta Horticulturae, **567**: 675–678.

Petrova, V., Samsone, I., Jankevica, L., and Cudare, Z. 2008. The predatory mite *Neoseiulus cucumeris* for control of the strawberry mite *Phytonemus pallidus* on strawberry runner plants. *In* Proceedings of international scientific conference "Sustainable Fruit Growing". *Edited by* Dimza, I.; Eihe, M.; Ikase, L.; Lanauskas, J.; Libiakova, G.; Lopez, M.; Stanys, V.; Tirzi¯tis, G.; Venskutonis, R. and Zurawicz, E.Latvia State Institute of Fruit-Growing. Dobele, Latvia. Pp. 250–256

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Raudonis, L. 2006. The effect of abamectin on strawberry mite *Tarsonemus pallidus* (Acari: Tarsonemidae) in strawberries. Sodininkystė ir daržininkystė, **25**: 153–161.

Rhodes, E.M., Liburd, O.E., Kelts, C., Rondon, S.I., and Francis, R.R. 2006. Comparison of single and combination treatments of *Phytoseiulus persimilis, Neoseiulus californicus*, and acramite (bifenazate) for control of twospotted spider mites in strawberries. Experimental and Applied Acarology, **39**: 213–225.

Rostami, N., Maroufpoor, M., Sadeghi, A., Ghazi, M.M., and Atlıhan, R. 2018. Demographic characteristics and population projection of *Phytonemus pallidus* fragariae reared on different strawberry cultivars. Experimental and Applied Acarology, **76**: 473–486.

Schaefers, G. 1963. Seasonal densities and control of the cyclamen mite, *Steneotarsonemus pallidus* (Acarina: Tarsonemidae) on strawberry in New York. Journal of Economic Entomology, **56**: 565–571.

Stenseth, C. and Nordby, A. 1976. Damage, and control of the strawberry mite *Steneotarsonemus pallidus* (Acarina: Tarsonemidae), on strawberries. Journal of Horticultural Science, **51**: 49–54.

Svensson B. 2008. Successful bio-control of the strawberry mite *Phytonemus pallidus* with the predatory mite *Neoseiulus cucumeris* in organic outdoor production of strawberries (*Fragaria*× *ananassa* Duch.) in Sweden. Acta Horticulturae, **842**: 657–660.

Tuovinen, T. and Lindqvist, I. 2010. Maintenance of predatory phytoseiid mites for preventive control of strawberry tarsonemid mite *Phytonemus pallidus* in strawberry plant propagation. Biological Control, **54**: 119–125.

Tuovinen, T., Lindqvist, I., Kauppinen, S., and Kivijarvi, P. 2009. Integration of biological mite control and conventional insect control in strawberry. Acta Horticulturae, **842**: 661–664.

Zalom, F.G., Thompson, P.B., and Nicola, N. 2009. Cyclamen mite, *Phytonemus pallidus* (Banks), and other tarsonemid mites in strawberries. Acta Horticulturae, **842**: 243–246. https://doi.org/10.17660/ActaHortic.2009.842.39.

Zhang, Z.-Q. 2003. Mites of greenhouses: identification, biology and control. Cabi Publishing, Cambridge, United Kingdom.

Figures

Figure 1. *Phytonemus pallidus* and the damage they cause. **A**, *Phytonemus pallidus* female and eggs inside a young strawberry leaf; **B**, adult *Neoseiulus cucumeris* feeding on a female *P. pallidus*; **C**, severe damage caused by *P. pallidus* on a strawberry plant (cultivar Jewel); **D**, damage caused by *P. pallidus* on a strawberry fruit. Photographs by Stéphanie Patenaude.

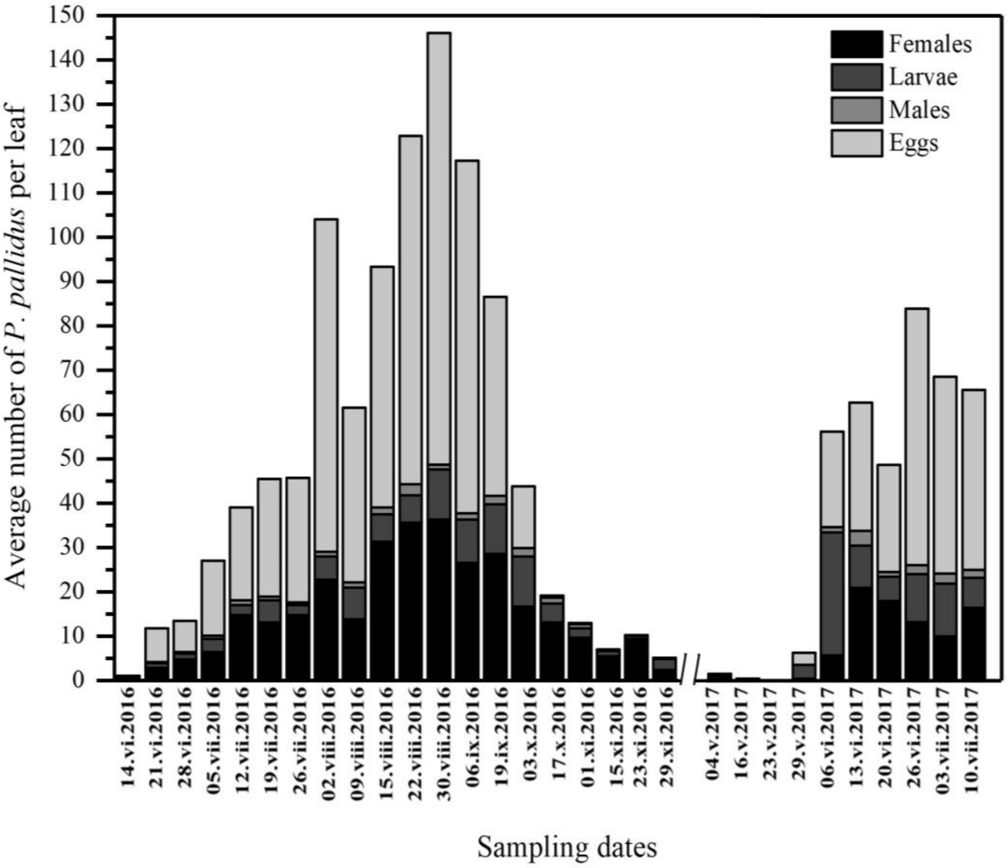


Figure 2. Dynamics of *Phytonemus pallidus* females, larvae, males, and eggs per young strawberry leaf for 2016 and 2017 weekly sampling in untreated plots in Sainte-Foy (Québec, Canada).

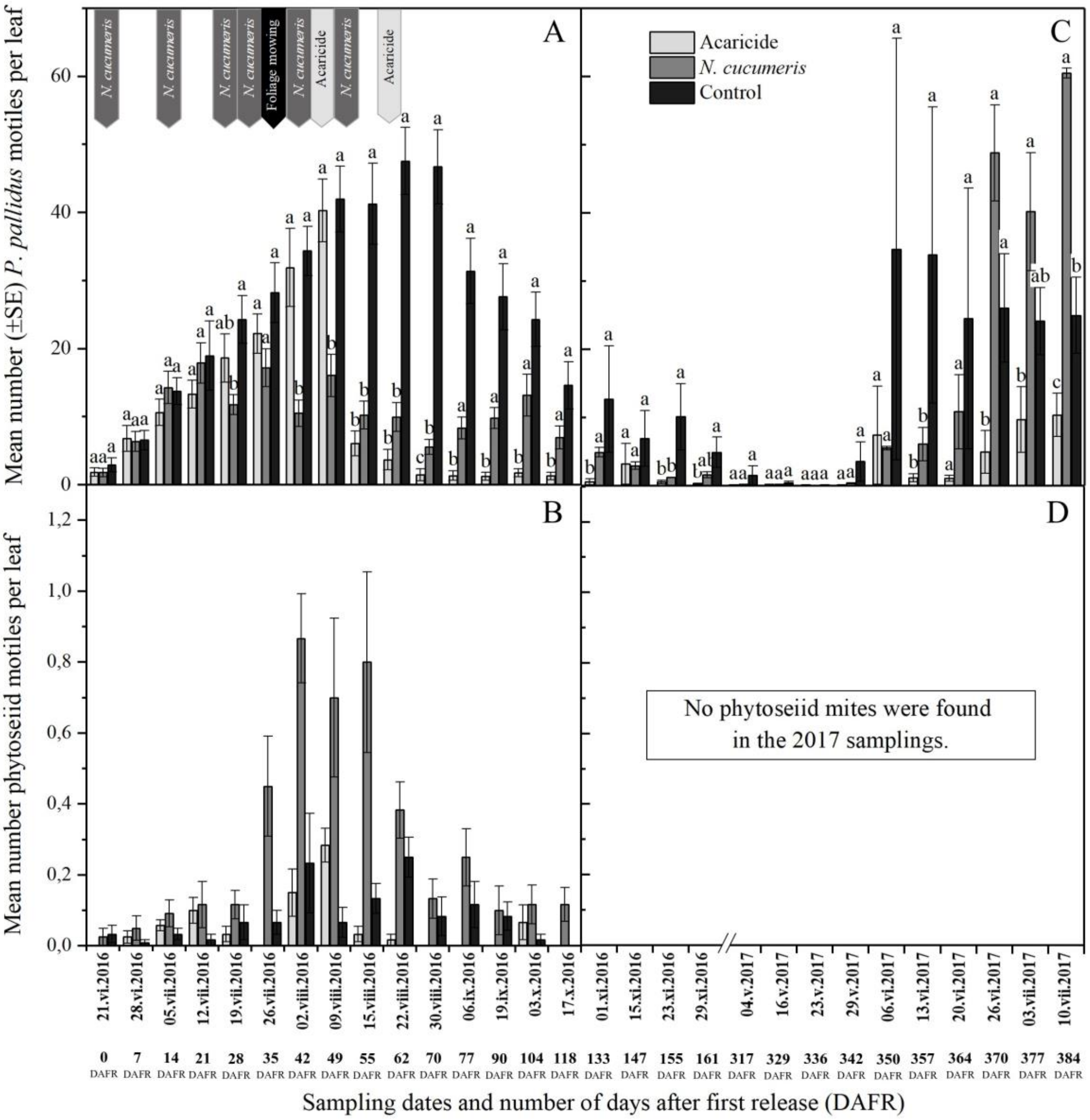


Figure 3. Average numbers (± standard error) of *Phytonemus pallidus* motile forms (Fig. A, C) and phytoseiid mite motile forms (Fig. B, D) per young leaf for the acaricide, *N. cucumeris* and control treatments on each sampling date for the in-field biological control experiment (Fig. A–B) and for the second-year follow-up observations of half of the plots (Fig. C–D). Dark-grey arrows show *N. cucumeris* release dates (21 June and 5 July: 500 *N. cucumeris* m^{-2}; 19 July, 26 July, 3 August,

and 10 August: 1000 *N. cucumeris* m^{-2}), light-grey arrows, acaricide applications and black arrow, foliage mowing (renovation). No predatory mite release or acaricide application was carried out in 2017. Columns with the same letters are not significantly different (protected least significant difference test, $P < 0.05$). No statistical test could be performed on the phytoseiid mite dataset due to the high proportion of zeros.

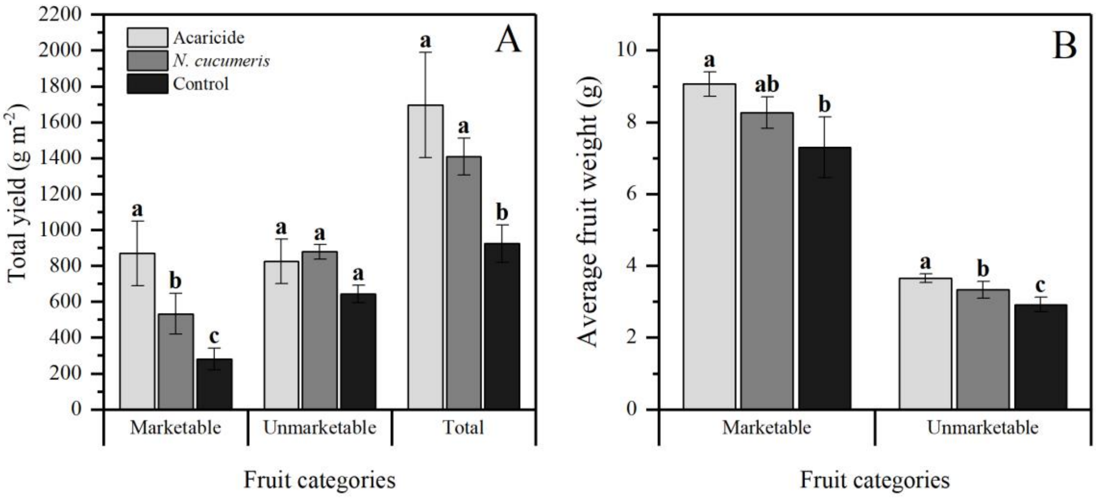
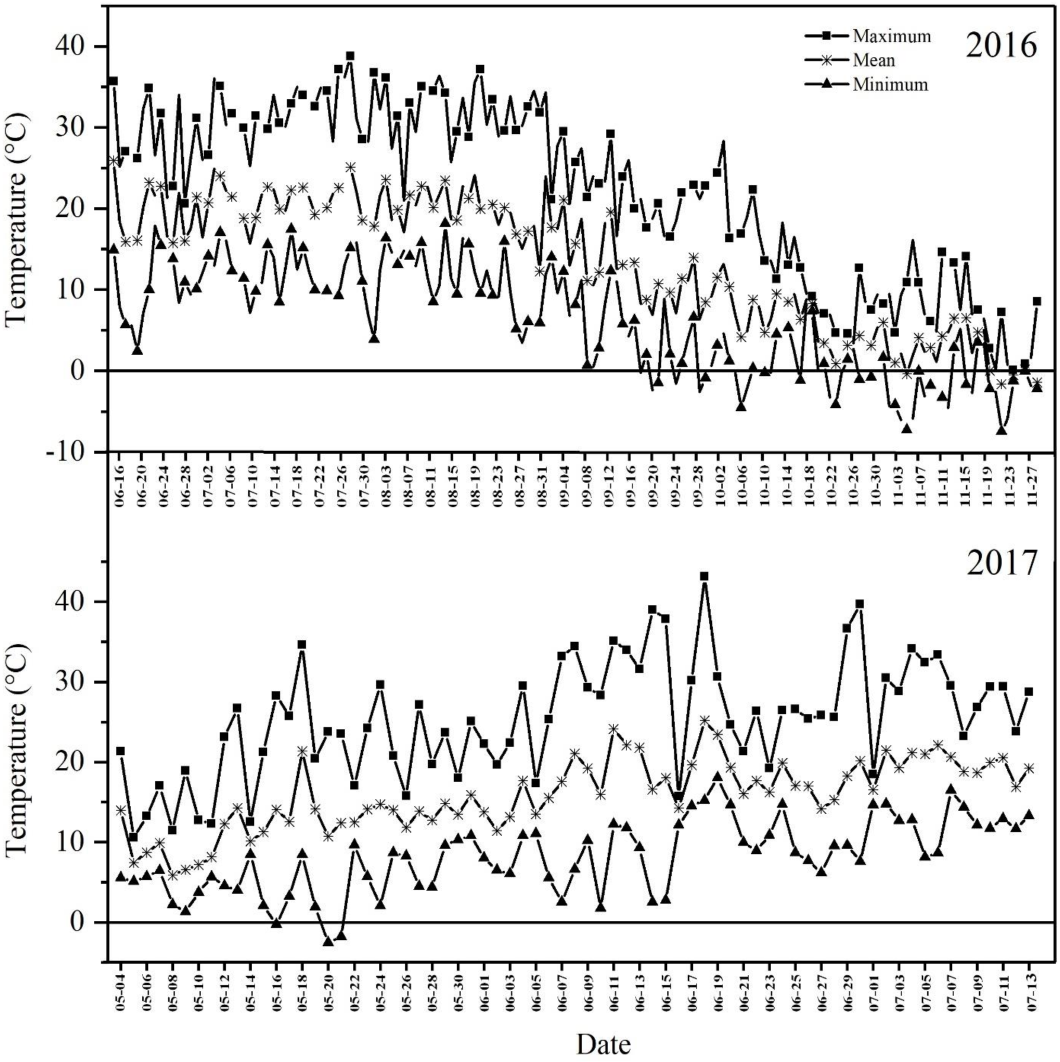


Figure 4. Strawberry yield for the three treatments (Acaricide, *N. cucumeris*, and Control) at the second-year follow-up (2017) of the 2016 in-field biological control experiment. Total yield (g m^2) (± standard error) and average individual fruit weight (g) (± standard error) of marketable, unmarketable, and total strawberries are shown in Fig. A and B, respectively. Columns with the same letters are not significantly different (protected least significant difference test, $P < 0.05$).

Supplementary material



Supplementary Figure 1. Average daily maximum, mean, and minimum temperatures from 16 June 2016 to 10 July 2017 as recorded by HOBO data loggers at canopy level in the experimental plots.