Climate change and potential selection for non-diapausing two-spotted spider mites on strawberry in southwestern British Columbia

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ABSTRACT

A validated model of the timing of post-diapause oviposition in the two-spotted spider mite, *Tetranychus urticae* Koch, was used to predict when 50% of strawberry leaflets with *T. urticae* also have *T. urticae* eggs ($IO_{0.5}$) in each year from 1954 to 2006 at Langley, British Columbia. This timing was studied in relation to hours of frost occurring before and after oviposition. Historically, $IO_{0.5}$ occurred before there were frost-free days, but there was a clear threshold at 390 h with temperatures < 0 °C after $IO_{0.5}$, which was not exceeded. This suggests that there is selection pressure for early oviposition, but also a limit to the extent of selection. The subzero temperature profile ~1 month before oviposition was clearly different from that after $IO_{0.5}$. The number of hours with subzero temperatures 1 month before oviposition, and the standard deviation of those estimates, were negatively correlated with year and indicated that there could be oviposition in January - rather than February - by 2015. Cumulative hours with temperatures < 0 °C between 27 November (the empirical estimate of the time when *T. urticae* begins accumulating degree-days for post-diapause oviposition) and 30 April was negatively correlated with year, and extrapolation of a linear regression suggested that there could be selection for continuous annual oviposition by 2050. There was considerable variation in the data, but considered in combination with published evidence for climate change, these results will be important in developing pest management strategies, and furthermore, will impact many aspects of agriculture in the Fraser Valley of British Columbia.

INTRODUCTION

Global warming (Intergovernmental Panel on Climate Change 2007) will probably affect arthropod ranges (Gray 2004; Logan and Powell 2004; Gutierrez et al. 2006; Musolin 2007) assuming fixed biological tolerances to environmental conditions. At the same time, within a home range, it will probably also affect the life history characteristics of arthropods through selection (cf. Bradshaw *et al.* 2004). Winter diapause is a key feature of temperate arthropods (Danks 2006). Diapause characteristics will probably be affected by global warming, and changes may become evident first in areas that have a relatively mild but temperate climate, such as the Fraser Valley of British Columbia (B.C.), Canada. This study considers the effects of climate change on the timing of initial, post-diapause oviposition (IO) by two-spotted spider mites, *Tetranychus urticae* Koch (Acari: Tetranychidae), on strawberry (*Fragaria* x *ananassa* Duch. Rosaceae).

T. urticae females have a facultative reproductive diapause. Diapause is induced in the pre-imaginal stages, particularly at the end of the protonymphal instar, by short-day photoperiods (Veerman 1977a). Termination is dependent on duration of cold rest, temperature, and photoperiod during the first few months of diapause (Veerman 1977b). During winter, after photoperiodic sensitivity is gone, diapause

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would be sustained and prolonged by low temperatures. Under long days at relatively high temperatures, diapause can be terminated without a cold rest period (Veerman 1977b), but under short days a cold rest period is required.

Given a warmer climate there should be selection for individuals who reproduce continuously, despite short days, and there may be selection for individuals who do not respond to the initial photoperiodic induction cues. This idea is supported by the fact that there is considerable variation in diapause induction and termination characteristics among *T. urticae* strains, probably associated with adaptation to local conditions (Takafuji *et al*. 1991; Koveos *et al.* 1999).

Raworth (2007) developed and validated a FORTRAN program (ProgIO) that determined the timing of post-diapause oviposition – the day when 50% of strawberry leaflets with *T. urticae* also had *T. urticae* eggs ($IO_{0.5}$). The oviposition model for the program was based on field samples from inland and coastal sites, collected during 1988 to 2006; estimates of $IO_{0.5}$ from 10 populations during 1988 to 2003 were used to calibrate the model, and six independent populations during 2004 to 2006 were used for validation.

Here, ProgIO and historical weather data are used to examine 1) where, historically, *T. urticae* has placed $IO_{0.5}$ with respect to frost, and 2) the annual historical trends in hours of frost. These trends are then used to predict when *T. urticae* can be expected to commence oviposition in January – rather than the current timing in February – and when *T. urticae* may go through the winter with no reproductive diapause. It may be objected that viable leaves must be available for feeding and oviposition; however, in this system mature green leaves overwinter, and the mites usually initiate feeding and oviposition on these leaves in February and March (Raworth 2007).

MATERIALS AND METHODS

ProgIO and meteorological data were used to predict $IO_{0.5}$ each year from 1954 to 2006. ProgIO first calculated the temperature under a strawberry leaf in a commercial field at Langley, B. C. based on hourly temperature and cloud opacity data measured by Environment Canada at Abbotsford, B. C. since 1953, and calibration equations (Raworth 2007):

1. Cloud opacity = 1 (full cloud)

a. 0800-1600 h: $y = -8.756 + 1.009\ t + 1.731\ h - 0.013\ t^2 - 0.076\ h^2 + 0.015\ t \times h$

$R^2 = 0.92, P < 0.0001$, 425 d.f.

b. 1700-0700 h: $y = -1.104 + 0.864\ t - 0.025\ h + 0.010\ t^2$

$R^2 = 0.92, P < 0.0001$, 862 d.f.

2. Cloud opacity = 0 (full sun)

a. 0800-1600 h: $y = -54.250 + 1.116\ t + 9.515\ h - 0.370\ h^2$

$R^2 = 0.85, P < 0.0001$, 241 d.f.

b. 1700-0700 h: $y = -3.848 + 1.153\ t + 0.066\ h + 0.023\ t^2$

$R^2 = 0.92, P < 0.0001$, 554 d.f.

where: y = temperature experienced by the mites; t = temperature in a Stevenson Screen in the field ($t = -1.141 + 1.043\ tec$, where tec = air temperature at the Environment Canada station); and h = hour (where: 0800-1600 h = 8, 9,...16; and 1700-0700 h = 17, 18,...24, 25, 26,...31). Temperatures under a leaflet in intermediate cloud conditions were determined by linear interpolation between the results provided by the equations for full cloud and full sun. The timing of $IO_{0.5}$ was then determined from thermal summations > 9.4 °C starting on an empirically-derived day, 27 November (Raworth 2007), and a thermal requirement (y) that was negatively correlated with accumulated cold-rest hours < 4 °C (x) summed from 27 November (Raworth 2007):

3. $y = 78.3 - 0.0279\ x$; $r^2 = 0.83, P = 0.01$, 4 d.f.

Equation 3 implies that, for equivalent rates of thermal summation, the spider mites will stay in diapause longer if they have had insufficient cold rest. The timing of $IO_{0.5}$ was compared graphically with the cumulative daily hours of frost below 0 ^oC summed between 27 November and 30 April of the following year.

To determine what temperature conditions the mites have avoided, annual frequency was plotted against the number of hours of frost below 0, -1, -2,…-10 ^oC that remained after $IO_{0.5}$ (3-d plot), and the hours of frost below 0, -1, -2,…-10 ^oC that occurred one month before mite eggs would be observed in the field, 10 January to 10 February (3-d plot). To determine when conditions would be suitable for earlier oviposition by *T. urticae*, the annual sum of hours of frost below 0, -2, -4,…-10 ^oC that occurred between 10 January and 10 February were regressed (SAS Institute 2004) against year and the regression was extrapolated beyond 2006. Changes in variability as a function of year were determined by pooling the latter data for each decade and regressing 1 SD for mean hours below a given temperature in that decade against the median year. Finally, a similar technique was used to determine when conditions would be suitable for *T. urticae* to pass through the winter without reproductive diapause based on the annual sum of the hours of frost below 0 ^oC between 27 November and 30 April.

RESULTS AND DISCUSSION

Cumulative hours of frost below 0 ^oC between 27 November and $IO_{0.5}$, from 1954 to 2006 varied between 400 and 1600 h (Fig. 1B, triangles). Despite this variation, $IO_{0.5}$ always occurred before frost-free days had begun (Fig. 1A, B), but with a clear upper threshold of 390 h of frost remaining after $IO_{0.5}$. This indicates sensitivity to frost, because all the estimates of $IO_{0.5}$ are clustered below 390 h; it also indicates some selection pressure for early oviposition, because the mites do not wait until frost-free conditions occur. As long as a female's progeny can survive and go on to reproduce, a female that initiates reproduction early in the season should have a numerical advantage over one that initiates reproduction later. This result should be qualified. The 390 h threshold was determined from a model of post-diapause oviposition in southwestern B. C.; it would not be expected to apply to *T. urticae* populations that are adapted to different local conditions in other temperate regions. Such a generalization would require further research.

Comparison of the subzero temperature profiles before and after $IO_{0.5}$ suggests that *T. urticae* in southwestern B. C. is able to tolerate >200 h at -2 ^oC, but only 20 h at -6 ^oC (Fig. 2). Lower temperatures for longer periods (Fig. 3) have been avoided. However, the number of hours with temperatures below 0, -2, … -10 ^oC, 1 month before *T. urticae* normally commences oviposition, have declined significantly since 1954 (Fig. 4). Taking -8 ^oC as a critical temperature associated with no oviposition (Fig. 2), the data indicate that an average year will have zero hours <-8 ^oC by 2015 (Fig. 4). At this time there could be reduced selection pressure against emergence, and hence oviposition in January rather than February. Because the regression predicts hours at a given temperature in an average year, one would expect some hours at temperatures <-8 ^oC in some years, and possible mortality of early-emerging mites. However, the variation in subzero temperatures during this 1 month period has also declined since 1954 (Fig. 5) so that there will be less uncertainty about subzero conditions in 2015 than there was in 1957, and reduced selection pressure against early emergence. The regression of total hours of frost below 0 ^oC from 27 November to 30 April against year suggests that the number of hours of frost will decrease to the threshold of 390 h by ~2050 (Fig. 6). At this point, selection for early oviposition could result in reproduction by some individuals right through the winter in southwestern B.C.

The objective of this study was to examine general patterns in the initiation of post-

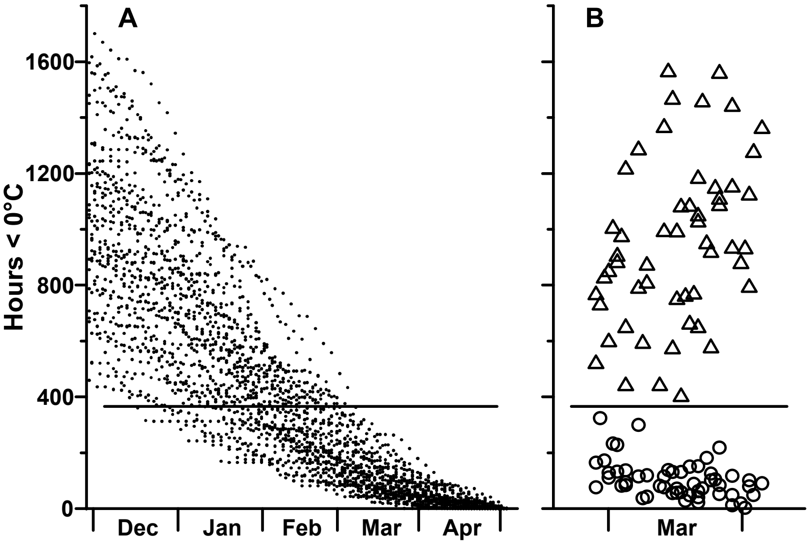

Figure 1. Cumulative hours with temperatures < 0 °C under a strawberry leaflet in a commercial field from: (A) start date to 30 April versus start date (dots); (B) 27 November to the date when 50% of strawberry leaflets with *T. urticae* also have *T. urticae* eggs ($IO_{0.5}$) versus $IO_{0.5}$ (triangles); and (B) $IO_{0.5}$ to 30 April versus $IO_{0.5}$ (circles), each year from 1954 to 2006. The horizontal line represents a threshold number of hours < 0 °C remaining after $IO_{0.5}$.

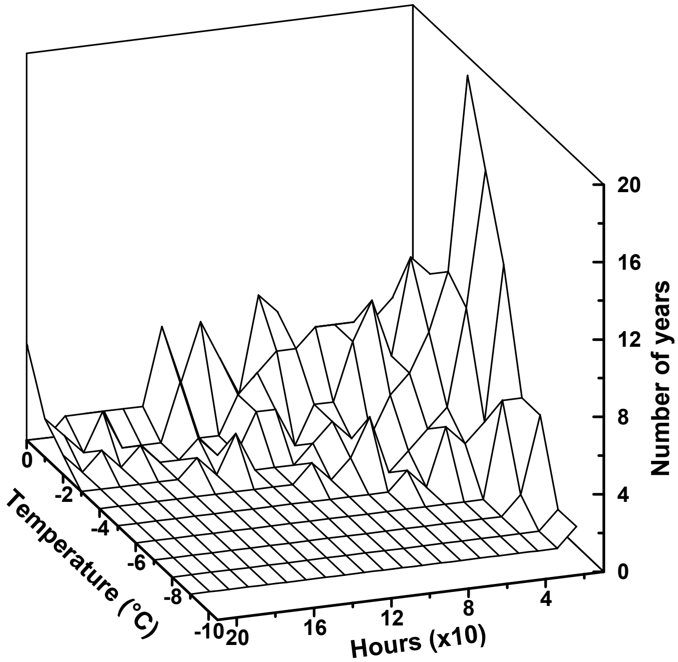

Figure 2. Number of years with a given number of hours at subzero temperatures under a strawberry leaflet in a commercial field, after the date when 50% of strawberry leaflets with *T. urticae* also have *T. urticae* eggs.

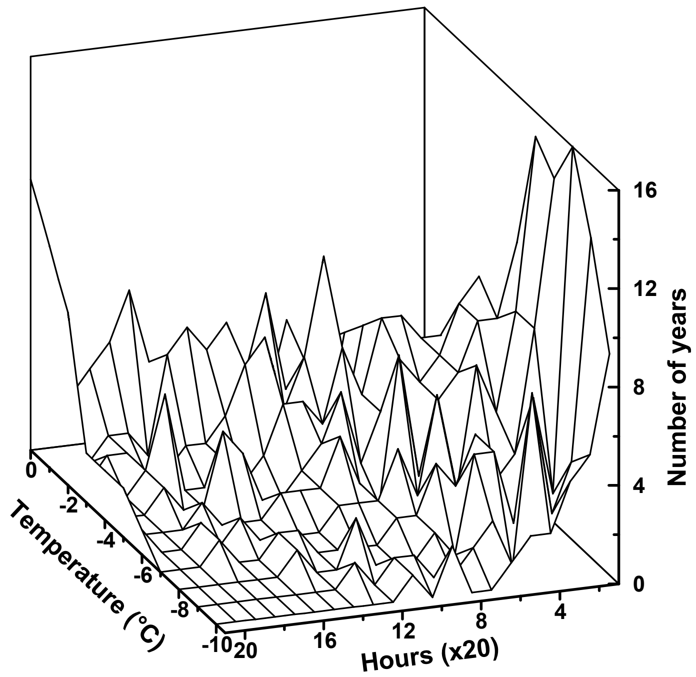

Figure 3. Number of years with a given number of hours at subzero temperatures under a strawberry leaflet in a commercial field, ~1 month before the date when *T. urticae* commences oviposition (10 January to 10 February).

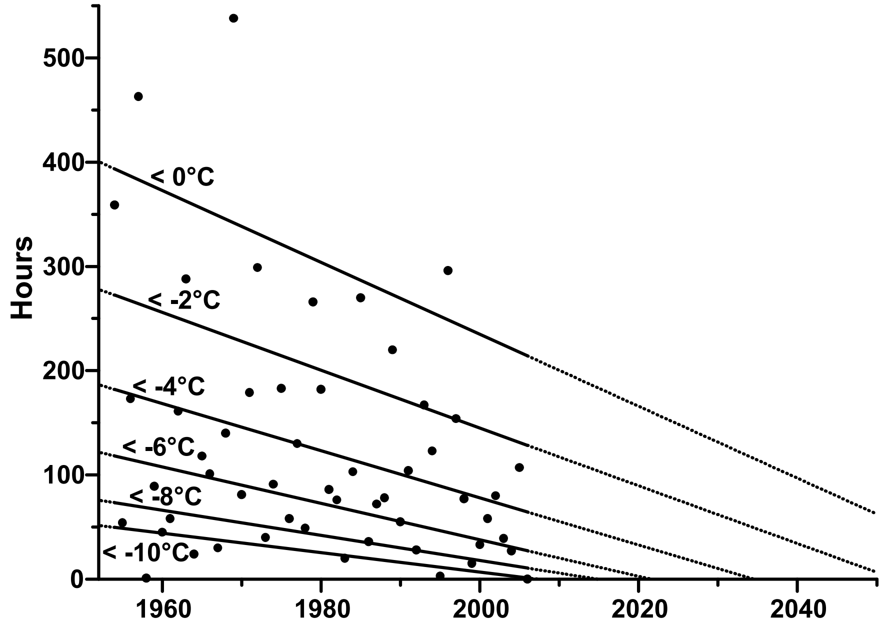

Figure 4. Hours with subzero temperatures under a strawberry leaflet in a commercial field, between 10 January and 10 February, versus year. Solid lines are linear regressions (r^2 = 0.10, 0.08, 0.08, 0.09, 0.10, 0.14 and P = 0.02, 0.03, 0.03, 0.02, 0.02, 0.004) for temperatures < -10, -8, … 0, respectively; data for temperatures <-4 °C are shown.

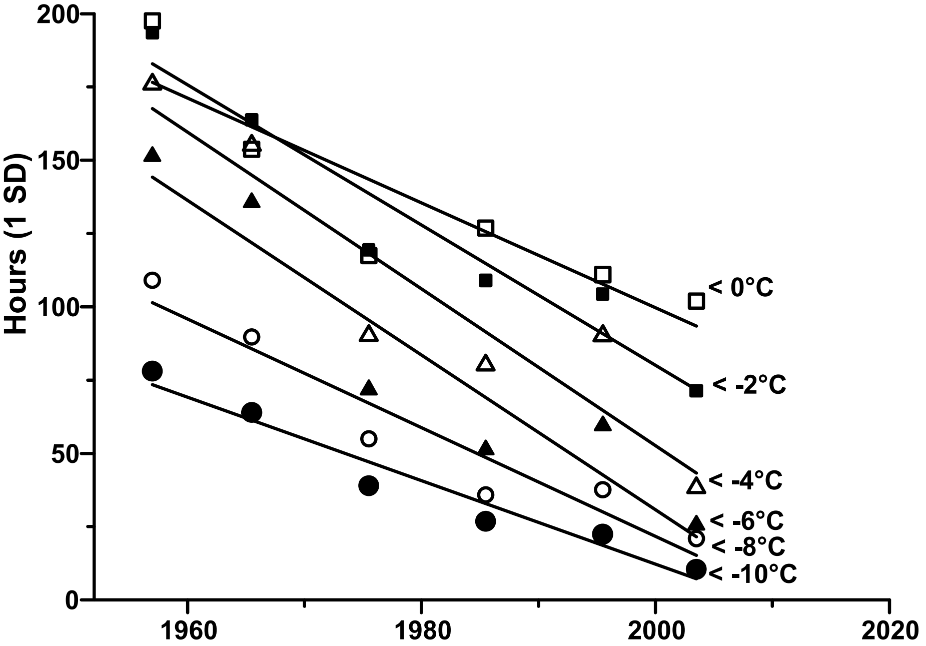

Figure 5. One SD of mean hours with subzero temperatures under a strawberry leaflet in a commercial field, between 10 January and 10 February, versus median year. Solid lines are linear regressions (r^2 = 0.95, 0.92, 0.89, 0.87, 0.93, 0.80 and P = 0.0008, 0.002, 0.005, 0.007, 0.002, 0.02) for temperatures < -10, -8, … 0, respectively.

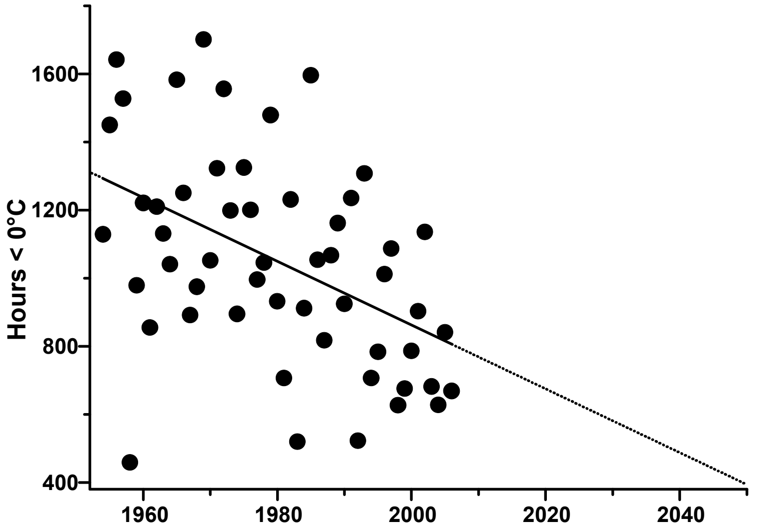

Figure 6. Hours with temperatures < 0 °C under a strawberry leaflet in a commercial field, from 27 November to 30 April, versus year. Solid line is a linear regression y = 19600. – 9.37 x; r^2 = 0.22; P < 0.001.

diapause oviposition in *T. urticae* in relation to field temperatures. A number of thresholds were observed for spider mite populations in southwestern B. C.: a maximum of 390 h of frost after IO$_{0.5}$; post-IO$_{0.5}$ tolerance to >200 h at -2 °C, but only 20 h at -6 ^{o}C; and -8 ^{o}C was taken as the critical temperature after $IO_{0.5}$ associated with no oviposition. These thresholds could be confirmed by further work, but this was not the point of the study; regardless of the exact value of the thresholds, the patterns are clear. Oviposition is initiated before frost-free days occur – in ProgIO and *ipso facto* in the field data used to build ProgIO; the number of hours of frost 1 month before oviposition, and variation in those estimates among years, has decreased significantly during the last half century; and the number of hours of frost from 27 November through 30 April have also decreased significantly over the years.

It is clearly risky to extrapolate from a linear regression based on data with considerable scatter (Figs. 4, 6); the relationship may be negative but asymptotic at, for example, 600 h frost (Fig. 6). However, there is additional evidence. Although it is difficult to attribute observed temperature changes to natural or human causes at smaller than continental scales because factors such as land use change and pollution complicate the picture (Intergovernmental Panel on Climate Change 2007), the trends observed in the current study are consistent with the global warming scenario. The mechanism driving global warming, namely increasing levels of greenhouse gases (GHG) (N_2O, CH_4, and CO_2) is well established, and 'With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades' (Intergovernmental Panel on Climate Change 2007); a global temperature change of +0.2 ^{o}C per decade is projected. Therefore, the linear extrapolations in Figs. 4 and 6 may be reasonable. Time will tell, however if correct, oviposition in January should be observable within the next decade.

Despite the many uncertainties in this study, there is sufficient evidence for earlier post-diapause oviposition in *T. urticae* within the relatively near future in southwestern B. C. to at least consider it in planning spider mite monitoring and management activities. This would evolve naturally into planning for continuous annual oviposition should that occur in 4 to 5 decades. Furthermore, a relatively rapid reduction in the number of hours of subzero temperatures during the winter will have significant implications for many aspects of agriculture in the Fraser Valley, including arthropod pest and disease management, crop production, and crop selection in both field and greenhouse environments. These effects need to be considered carefully by growers, pest managers, researchers, and government planners at Provincial and Federal levels with studies and approaches to address potential problems evolving as trends become increasingly certain.

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