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The effect of temperature and light conditions on diapause induction in a Korean population of *Neoseiulus womersleyi* Schicha (Acari: Phytoseiidae)

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ABSTRACT

To determine the condition for diapause induction of a Korean population of *Neoseiulus womersleyi*, combinations of constant temperatures (14, 16, 18, 20 and 25 °C) and photoperiods (0, 8, 10, 12, 14, 16 and 24 h photophase) were used from egg to adult emergence. Diapause induction was determined by reproductive cessation of adult females. Lower temperature and shorter photophase resulted in higher diapause induction. Critical photophases for diapause induction were 10 and 12 h at 18 and 16 °C, respectively. Diapause-induced *N. womersleyi* adult females consumed significantly fewer eggs of the two-spotted spider mite, *Tetranychus urticae*, than non-induced females. Field monitoring of *N. womersleyi* showed that there was no egg-bearing female after 282 Julian date, while a model estimated complete diapause induction at 288 Julian date. Diapause of this predatory mite occurred approximately 2 weeks before diapause of its main prey, *T. urticae*, in Korean apple orchards. Further study perspectives are discussed relative to the spider mite biological control system in fruit orchards.

Introduction

Neoseiulus womersleyi Schicha is an important predator of the two-spotted spider mite, *Tetranychus urticae* Koch, in Korean apple and pear orchards (Jung et al., 2003; Jung and Lee, 2004). With high prey consumption rate and fast development, *N. womersleyi* is considered a potential biological control agent of *T. urticae* (Lee et al., 1987; Kim and Lee, 1993, 1994; Kim et al., 1996; Lee and Ahn, 2000). Research on mite control has focused on utilizing this predatory mite in apple and pear orchards in Korea (Lee, 1990; Han et al., 2003; Jung et al., 2003, 2004). However, persistent mite control by *N. womersleyi* has not yet been achieved in Korea. One problem is that even if *N. womersleyi* successfully controls the spider mite population in the previous year, field occurrence of this predator the following year appears too late in the season on ground vegetation and in the apple tree canopy. To establish a successful biological control system of *T. urticae*, it is essential that *N. womersleyi* survives during winter and occurs the next spring. However, winter mortality of *N. womersleyi* and *T. urticae* is high in Korean apple orchards (Kim et al., 2004).

In apple and pear orchards, *N. womersleyi* overwinters mostly on ground vegetation (Kim et al., 2004). *N. womersleyi* enters reproductive diapause in response to short photoperiod and low temperature (Hamamura, 1982, 1986; Kishimoto and Takafuji, 1994, 1997; Maeda et al., 2000), which is similar to what occurs in other phytoseiids, such as *Metaseiulus* (=*Galendromus*) *occidentalis* (Hoy, 1975a,b), *Typhlodromus pyri* (Fitzgerald and Solomon, 1991), and *Neoseiulus cucumeris* (Morewood and Gilkeson, 1991). Diapause is characterized as non-gravidity in inseminated females and lowered prey consumption (Putman, 1962; Hoy, 1975a,b; Swift, 1987). Conditions for diapause induction of the Japanese population of *N. womersleyi* are available (Hamamura, 1982). However, even within the species, the diapause response may vary depending on strain or population (Croft, 1971; Veerman, 1992). Because there is no information on diapause induction of the Korean population of *N. womersleyi* with respect to temperature and photophase, we evaluated the effects of temperature and photoperiod on diapause induction of *N. womersleyi* in the laboratory and examined field populations of *N. womersleyi* and *T. urticae* for their timing of diapause.

Materials and methods

Mite colony

A laboratory colony of *N. womersleyi* was originally collected from an apple orchard at the National Horticultural Research Institute (NHRI, N37°15′50″, E126°58′24″) in Suwon, Korea, on June 25, 2002. It was maintained on kidney bean plants (*Phaseolus vulgaris* var. *humilis*) with *T. urticae* prey at 25 ± 3 °C, 60–80% RH, and a photoperiod of 16:8 (L:D) h.

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Diapause induction experiment

A series of temperature and photoperiod combinations were examined to determine the critical temperature and photoperiod for diapause induction of *N. womersleyi.* A kidney bean leaf was placed bottom-side up on a water-saturated cotton in a plastic tray (16×23×4.5 cm). To obtain *N. womersleyi* eggs, 40 to 50 female adult *N. womersleyi* were isolated from the laboratory colony and transferred to detached bean leaves with *T. urticae* for 24 h at 25 °C and then removed. Eggs of *N. womersleyi* were subjected to multiple combinations of temperature (14, 16, 18, 20, and 25 °C) and photoperiod (24:0, 16:8, 14:10, 12:12, 10:14; 8:16, and 0:24 (L:D) h). A mixture of different stages of *T. urticae* was provided as food until *N. womersleyi* maturation. Within 5 days after adult *N. womersleyi* emergence, females were transferred individually onto bean leaf discs (2.5 cm diameter) where eggs of *T. urticae* were provided as food. One or two male *N. womersleyi* were added to ensure mating. Oviposition was checked under a stereomicroscope (40×) daily during the light period. Diapause of *N. womersleyi* was determined by oviposition failure for 8 consecutive days. Daily prey consumption of diapausing and non-diapausing female was also examined under the same conditions.

Field survey

The diapause status of *N. womersleyi* in the apple orchard was monitored 8 times each in 2002 and 2003. Monitoring was done from 4 September to 10 December at weekly intervals in an experimental apple orchard of NHRI, Suwon. Because direct determination of diapause of *N. womersleyi* was difficult, we employed an indirect measure (Veerman, 1992). All predatory mites found were slide-mounted and examined for a simple indicator of gravidity of adult female *N. womersleyi* through the late season. Diapausing females of phytoseiid mites were distinguished from non-diapausing females by the lack of eggs inside the abdomen (Hoy, 1975a,b; Veerman, 1992). Additionally, the percentage of the diapausing form (orange colored) of *T. urticae* was monitored in the same orchard in 2003. Daily minimum, maximum, and average air temperatures were obtained from a weather station located ca. 1 km away from the orchard. Photoperiod data were obtained from Korean Astronomical Almanac of Korea Astronomy Observatory as a photophase between the sunrise and sunset.

Data analysis

Effects of temperature and photoperiod on prey egg consumption by diapause-induced and non-induced female mites were analyzed by GLM and *t*-test using SAS (ver. 8.02; SAS, 2004). A numerical model was constructed for diapause induction from a quadratic regression of temperature and photoperiod as independent variables. Because of the lower numbers of *N. womersleyi* collected from the experimental apple orchard, field monitoring data from 2002 and 2003 were pooled together into the Julian date.

Results

Diapause induction in the laboratory

Lower temperatures and shorter photoperiods resulted in a higher rate of diapause induction of *N. womersleyi* (Table 1). The critical photoperiod (50% diapause induction) appeared to be 12–14 h at 16 °C and 10–12 h at 18 °C. At 14 °C, *N. womersleyi* entered into diapause regardless of the photoperiod. At 20 °C, incidences of diapause were very low and, at 25 °C, no females entered into diapause.

Induction of diapause was influenced significantly by temperature and photoperiod; the temperature effect was negative nonlinear and the photoperiod effect was negative linear to the diapause induction of *N. womersleyi* (GLM, df = 3,29, P<0.0001, r^2 = 0.699) (Eq. (1) and Fig. 1). The diapause induction of *N. womersleyi* increased as temperature and photoperiod decreased

$$D = 493.67 - 36.7 \times T + 0.73 \times T^2 - 2.48 \times P \quad (1)$$

where % diapause induction (D) is a function of T (temperature, °C) and photoperiod (h) in a day (P).

Even though diapause-induced female consumed prey eggs, their consumption was significantly lower than non-induced female, regardless of the temperature (*t*-test: P< 0.001; Table 2). While diapause-induced adult female *N. womersleyi* consumed only 0.3–2.9 *T. urticae* eggs per day, non-diapausing females consumed 5.5–18.1 *T. urticae* eggs, depending on temperature. Among diapause-induced female groups, egg consumption was highest at 14 °C (GLM, df = 3,108, P<0.01). Consumption rates of diapause non-induced female increased as the temperature increased (GLM, df = 3,164, P<0.001). There was no general pattern of prey egg consumption rate at different photoperiods.

Diapause incidence in the field

During September (243–274 Julian date), the percentage of non-gravid female *N. womersleyi* fluctuated between 30% and 66% in the apple orchard. In the first week of October (275–282 Julian date), 94.7% of adult females were gravid (Fig. 2). Within this period, the average temperature and photophase changed from 17.5 to 15.4 °C and from 11.6 to 11.3 h, respectively. From the model (Eq. (1)), 50–75% diapause induction was expected during 272–283 Julian date. The percentage of the diapausing (orange colored) form of *T. urticae*

Table 1
Diapause induction (%) of adult female *Neoseiulus womersleyi* reared from egg to adult under constant temperatures and photoperiod regimes.

Temperature (°C)	Photophase (h/day)						
	24	16	14	12	10	8	0
14	78.57 (14)[b]	75.00 (4)	–[a]	89.47 (19)	–	100 (11)	100 (22)
16	9.09 (11)	0.00 (28)	40.00 (10)	100 (13)	100 (40)	100 (10)	100 (26)
18	0.00 (16)	19.44 (36)	3.92 (51)	4.17 (48)	100 (14)	80.00 (40)	95.35 (41)
20	0.00 (16)	5.56 (18)	9.09 (11)	22.22 (18)	7.32 (41)	5.41 (74)	41.38 (53)
25	0.00 (21)	0.00 (32)	–	0.00 (23)	–	0.00 (28)	0.00 (30)

[a] No data.
[b] Numbers in parentheses indicate number of surviving and remaining females on the test arena. Initially ca. 100 eggs were treated at each condition.

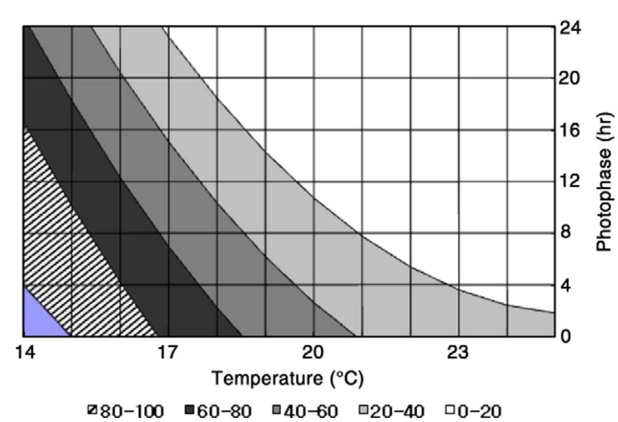

Fig. 1. Estimated diapause induction (%) of *Neoseiulus womersleyi* based on quadratic regression analysis by temperature and photoperiod (Eq. (1)).