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The effects of temperature, relative humidity and host plant on the behaviour of *Stethorus punctillum* as a predator of the two-spotted spider mite, *Tetranychus urticae*

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Abstract. The predatory behaviour of *Stethorus punctillum* larvae was studied on the two-spotted spider mite (*Tetranychus urticae*), in order to assess how it responded to temperatures and relative humidities typical of glasshouse conditions on four edible crop plant species. Locomotory activity (distance covered, time spent walking, walking speed, angular velocity, and turning rate) was recorded at 20, 25 and 30 °C and relative humidity levels of 33%, 65% and 90% RH on tomato, pepper, aubergine and cucumber and analysed using video/computer techniques. The results show that activity of *S. punctillum* significantly increased at higher temperatures. Host plant species also strongly influenced the performance of the predator, which was most active on pepper and tomato and least active on aubergine. Relative humidity had no significant influence.

Key words: biological control, locomotory and predatory activity, Acari, Coccinellidae, Coleoptera, Tetranychidae

Introduction

The two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae; TSSM) is a serious pest on over 30 economically important crops, including corn, cotton, cucumber, beans, tomato, aubergine, peppers and a variety of greenhouse ornamentals (Helle and Sabelis, 1985a,b). Since TSSM feeds on the chlorophyll, water and nutrients from leaf cells the occurring foliar damage results in lost of yield or even in the death of the plant. Current advances in the biological control of pests in glasshouses relies on the so-called 'magic bullet' approach with the use of just one or two 'best' species of natural enemy as biocontrol agents. For example, current glasshouse biological control of TSSM relies on regular prophylactic introductions of *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae). Whilst this is effective most of the time, occasional failures occur due to factors which are often poorly understood. These may include differences in the response to seasonal changes in temperature, humidity and light levels between the natural enemy and pest species and/or host plant effects (Nihoul, 1992, 1993a,b). The indications are, therefore, that biocontrol agents in addition to *P. persimilis* may be required to successfully manage TSSM in glasshouses.

All known species of the genus *Stethorus* Weise (Coleoptera: Coccinellidae) are predators of spider mites (McMurtry et al., 1970; Hoy and Smith, 1982; Chazeau, 1983; Charles et al., 1985; Bailey and Caon, 1986; Felland and Hull, 1996) and several species have been suggested to have potential as biological control agents of spider mites in agricultural crops (Readshaw, 1975; Hull et al., 1976, 1977; Roy et al., 1999). Most of these studies conclude that species from the genus *Stethorus* are ‘high density predators’, since the female needs abundant spider mite supplies before ovipositing (Putman, 1955; McMurtry and Johnson, 1966; McMurtry et al., 1970). However, some of the characteristics of *Stethorus* spp. indicate considerable biocontrol potential: they are voracious obligate spider mite predators with long-lived adults (Putman, 1955) that are capable of effective dispersal (McMurtry and Johnson, 1966; Congdon et al., 1993).

Fleschner (1950) investigated the searching capacity of *Stethorus* species and determined that prey detection appears to occur by direct physical contact. For example, a study of *S. punctillum* by Putman (1955) showed that adults and larvae appeared to locate their prey at random in peach orchards. However, Hull et al. (1977) found that *S. punctum* (LeConte) managed to detect very low mite densities, suggesting that the predator might use some other stimulus other than random searching to find mites. Congdon et al. (1993) showed that *Stethorus punctum picipes* Casey is adapted to exploit spider mite populations by actively locating rare patches early in the season when both predator and prey populations are low. Congdon et al. (1993) conclude that the effectiveness of *Stethorus* sp. as a biocontrol agent may not primarily be based on a numerical response (as it is for phytoseiid predators (McMurtry, 1982)), but rather through its capability of locating small prey patches and its dispersal ability.

Most studies, however, concentrate on the efficacy of *Stethorus* sp. in orchards (Putman, 1955; Hull et al., 1977; Congdon et al., 1993; Felland and Hull, 1996; Roy et al., 1999) and little research has been done in the field of glasshouse biocontrol. The *Stethorus* species are relatively small and remarkably well adapted to live and search for prey in the habitats of plant-feeding mites (Kapur, 1948). Therefore the addition of a winged predator that could move rapidly to spider mite ‘hot spots’ would be useful. This study is part of a UK Ministry of Agriculture, Fisheries and Food project aiming to improve the control of *T. urticae* by using a complex of predatory species. This paper looks at the predatory behaviour and activity of *Stethorus punctillum* Weise larvae on TSSM to assess how it responds to environmental factors and host plant species typical of glasshouse conditions.

Materials and methods

Experiments were conducted from January 1999 to March 1999. TSSM colonies were reared on broad beans (*Vicia faba* L.). The TSSM were reared in a glasshouse between 25 and 30 °C with a 16L:8D photoperiod. The relative humidity fluctuated between 40% and 70%. Additional TSSM colonies were also reared on tomato (*Lycopersicon esculentum* Miller: cvs. Solairo and Ailsa craig), pepper (*Capsicum annuum* L.: cv. Bell boy), aubergine (*Solanum melongena* L.: cv. Moneymaker) and cucumber (*Cucumis sativus* L.: cv. Tyria) to ensure that the TSSM used for the experiments were acclimated to the host plants. The *Stethorus punctillum* cultures were reared on TSSM infested broad bean leaves in a controlled temperature room at 25 °C (± 1 °C) and RH of 50–60%.

The behaviour of individual predators was observed on 10 mm^2 discs cut from non-infested leaves of the host plant species being tested. For each predator observed, a freshly cut leaf disc was floated, bottom-side up, in a Petri dish covered with a filter paper and filled with water; this kept the leaf disc from drying out too quickly and inhibited mite and predator emigration from the leaf disc (see leaf-island method; Sengonca and Gerlach, 1983). Experiments were conducted in incubators kept at three different temperature levels (20, 25 and 30 °C). Humidity chambers were constructed from transparent plastic boxes measuring 270 mm × 160 mm × 100 mm. Saturated salt solutions of $MgCl_26H_2O$, $NaNO_2$ and KNO_3 were used within individual boxes to maintain constant humidities of 33%, 65%, and 90%, respectively (Winston and Bates, 1960). Within each box, 4 small glass-tubes held a 15 cm × 20 cm piece of vinyl tile above the salt solutions, and the Petri dishes containing the leaf discs were placed on these tiles.

Predator activity

Predator behaviour was observed on TSSM infested leaf discs. Ten immature TSSM deutonymphs were taken from the leaves of the colony and placed on the leaf disc 24 hours prior to the trial observations. This ensured that all leaf discs had approximately the same condition at the beginning of the observations. Freshly emerged 3rd instar *S. punctillum* larvae (3 mm) were used for the trials. Each larva tested was starved for 24 h prior to the experiments to standardise the condition of the predator. The larva was placed on the leaf disc and allowed to acclimatise for 30 min to the arena and the temperature/humidity conditions before recording data. Each predator was observed individually for a period of 10 min using a high resolution video camera. The following locomotory parameters were measured using Micromeasure V3 (a computer/video measurement package; Varley et al., 1994): distance covered, time spent walking, walking speed (distance walked/time spent walking), angular velocity (degrees per second), and turning rate (degrees turned mm^{-1} calculated as an average over a 5 mm sampling distance). Observations were also made on general predator activity for each plant species (scoring numbers of prey encountered, killed and eaten, changes in searching behaviour on encountering prey, attempts to disperse). Fifteen trials were carried out for each plant species at each temperature and RH using a factorial design, with no individual being tested more than once.

Unless otherwise stated, all results were tested using a factorial analysis of variance. Table 1 shows pooled data for each main effect. Differences between means of activity were calculated using Tukey's honest significance test at the 5% level.

Results

A three-way factorial analysis of variance, between the plant species, RH and temperature, showed that most of the observed locomotory activities, such as distance covered, walking speed and percent of time spent moving, were significantly influenced by the main effects: temperature levels ($p < 0.01$) and crop plant species ($p < 0.05$). Relative humidity caused a significant decrease only in the walking speed ($p < 0.01$) at 65% RH. Of the two-way interactions, the interaction between plant species and temperature showed a significant increase in activity (turning rate, walking speed, and number of prey encountered; $p < 0.01$), whilst distance moved was significant in the three-way interaction ($p < 0.05$). The main effects of each factor are shown in Table 1.

Looking at each main effect separately showed that apart from reduced walking speed at 65% RH ($p < 0.05$), *S. punctillum* showed no significant change of locomotory and predatory activity under different relative humidity conditions. However, there was a trend towards increased locomotory activity at 33% and 65% RH (see Table 1).

At different temperature levels (Table 1), *S. punctillum* responded with a significant increase in distance covered ($p < 0.01$), turning rate ($p < 0.01$), angular velocity ($p < 0.01$), speed of walking ($p < 0.01$) and percentage of

Table 1. Mean of observed behaviour of *S. punctillum* (± SE) on leaf discs with TSSM as prey (pooled data for each main effect)

		Distance (mm) moved in 10 min	Angular velocity (° s^{-1})	Turning rate (° mm^{-1})	Walking speed (mm s^{-1})	Time moving (%)	Prey encountered	Prey eaten
*	20°C	12.9 ± 1.06a	10.1 ± 0.71a	3.51 ± 0.41a	0.47 ± 0.01a	6 ± 0.5a	0.68 ± 0.06a	0.41 ± 0.04a
	25°C	22.6 ± 2.11b	12.9 ± 0.93ab	5.50 ± 0.48b	0.52 ± 0.01b	8 ± 1.0b	0.73 ± 0.08a	0.39 ± 0.04a
	30°C	21.2 ± 1.88b	13.9 ± 0.92b	6.34 ± 0.47b	0.53 ± 0.01b	7 ± 1.0ab	0.72 ± 0.06a	0.46 ± 0.04a
*	33% RH	21.4 ± 2.02a	13.3 ± 0.93a	5.46 ± 0.47a	0.52 ± 0.01ab	8 ± 0.8a	0.79 ± 0.08a	0.47 ± 0.04a
	65% RH	18.7 ± 1.76a	12.6 ± 0.86a	5.61 ± 0.47a	0.48 ± 0.01a	7 ± 0.6a	0.69 ± 0.07a	0.41 ± 0.04a
	90% RH	16.5 ± 1.47a	10.9 ± 0.8a	4.29 ± 0.44a	0.53 ± 0.01b	6 ± 0.6a	0.64 ± 0.06a	0.38 ± 0.04a
**	Tomato	24.3 ± 2.73a	15.1 ± 1.21a	5.23 ± 0.49a	0.40 ± 0.01a	11 ± 1.0a	1.44 ± 0.11a	0.68 ± 0.05a
	Pepper	24.7 ± 2.50a	12.8 ± 1.04a	5.64 ± 0.54a	0.54 ± 0.01b	8 ± 0.8a	0.85 ± 0.07b	0.55 ± 0.04a
	Aubergine	10.9 ± 0.76b	8.97 ± 0.77b	3.93 ± 0.52a	0.53 ± 0.01b	4 ± 0.4b	0.30 ± 0.04c	0.26 ± 0.04b
	Cucumber	15.7 ± 1.20b	12.3 ± 0.86ab	5.66 ± 0.56a	0.57 ± 0.01b	5 ± 0.4b	0.24 ± 0.04c	0.19 ± 0.03b

Means within a treatment followed by the same letter are not significantly different at $p = 0.05$ (Tukey's Test; * range = 3.34; ** range = 3.65; 540 d.f.).

time spent moving ($p < 0.05$) with rising temperatures (i.e. 25–30 °C). The increased locomotory activity at higher temperatures, however, did not result in a significant increase of encountering prey or number of prey killed.

Table 1 shows that there was significantly higher locomotory activity on pepper and tomato plants when compared to aubergine and cucumber. However, there were no significant differences in distance covered, and turning rate between tomato and pepper and between aubergine and cucumber. Walking speed was lowest on tomatoes ($p < 0.05$). The increased locomotory activity resulted in increased prey encounter and number of prey killed ($p < 0.01$) (Table 1). General observations showed that the *S. punctillum* larvae had great difficulties moving on an uneven surface. Hence the pepper leaf offered the most beneficial surface for movement.

Discussion

The results of this study showed that the locomotory and predatory activity of *S. punctillum* is strongly influenced by temperature and host plant species (i.e. the leaf surface), whilst relative humidity had little effect on such behaviour. There are few studies that examine temperature levels, and even fewer investigating relative humidity levels, and of these, most only described the rearing conditions of *Stethorus* spp. Various studies, for example, investigated the life history of *Stethorus* spp.: Putman (1955) reared *S. punctillum* in the laboratory at 22 °C and 79% RH, Houck (1986, 1991) recorded prey preferences, time- and resource-partitioning of *S. punctum* (LeConte) at 24 °C and 70–80% RH, while other studies kept the *Stethorus* spp. cultures at 25–27 °C and 50–65% RH (Scriven and Fleschner, 1960; Tanigoshi and McMurtry, 1977). Overall, most studies only considered a single temperature, at around 25–27 °C. Relative humidity conditions vary considerably in these studies, indicating that other factors override any effect the relative humidity may have on the development of *Stethorus* spp. This agrees with the current study where *S. punctillum* showed increased predatory behaviour at 25–30 °C, but not with increased relative humidity conditions. The increased activity at higher temperatures is consistent with population data which show the range of this species in Britain to be restricted to a few localities in S.E. and central southern Britain (Majerus, 1994). Other studies investigating the effect of temperature on coccinellid species, showed increased fecundity and ovipositon at increasing temperatures up to 30 °C (Ponsonby and Copland, 1998), or increased larval developmental rate at around 28 °C (Ponsonby and Copland, 1996; LaMana and Miller, 1998). This indicates that temperature levels influences predation, reproduction and development of coccinellids, and that the thermal requirements of each coccinellid species has to be considered for use in biological control programmes (Obrycki and Kring, 1998).

The lack of response of *S. punctillum* to the different humidity conditions may be influenced by the experimental set up, i.e. leaf discs were floated on water. Therefore the humidity experienced by the larvae, on the leaf near the water, could have been different from that in the airspace of the chamber (which was permanently recorded), thus resulting in no variation in humidity experienced by the larvae. However, another study (using the same experimental set up) investigating the locomotory activity of a predatory mite, *Amblyseius californicus* McGregor (Acari: Phytoseiidae) at different environmental conditions (Rott and Ponsonby, 1998), showed significantly higher activity at low RH levels. This indicates that the method used, is accurate enough to show a response of the predator to humidity changes in the chamber.

The leaf surface appears to be an important factor when assessing predator activity (Southwood, 1986; Nihoul, 1993a; Roy et al., 1999). Putman (1955) reported that leaves with trichomes damage the integument of coccinellids, thus decreasing their mobility, while Obrycki (1986) reported that searching behaviour of coccinellids is influenced by the complexity of the substrate searched. Heinz and Parella (1994), for example, noticed a significant reduction in predation of whitefly by its coccinellid predator as poinsetta leaf trichome density increased. In the current study, aubergine plants, and to a lesser extent, cucumber plants appear to have the least favourable leaf surface for *S. punctillum* larvae. Locomotory activity was reduced, with less time spent moving and less distance travelled. In fact, it was frequently observed that the larvae would stay on one spot and display only sweeping movements of the head, explaining the comparatively high turning rates. These results tend to confirm observations in the crop situation whereby TSSM is usually completely controlled by biocontrol agents in pepper whereas control often fails or breaks down, in tomato or cucumber and aubergine respectively, thus requiring the use of pesticides (John Dale, BCP Ltd., Wye, UK, 1999, personal communication). Uncontrolled field trials in glasshouses in British Columbia, Canada have shown *S. punctillum* to be promising predator on cucumber and pepper, particularly at low densities, being able to seek out isolated outbreaks of mites (D. Elliot, Applied Bionomics, Canterbury, UK, 1999, personal communication).

However, since laboratory findings can often be completely different to the situation in the field (Force, 1974; Ehler and Hall, 1982), the results of this study are currently being extended by simulated field trials to better understand the factors affecting the efficacy of *S. punctillum* as a biocontrol agent in glasshouses, as well as investigating multi-species predator releases. Other multi-species release studies (Laing and Huffaker, 1969; Oatman et al., 1977; Ehler, 1992; Croft and Slone, 1997) suggest that this kind of approach is more efficacious than single predator releases and that intespecific competition only occurs after the TSSM population has crashed. Preliminary results indicate that multi-species predator releases that include the voracious *S. punctillum* have the potential for greatly improving the control of TSSM in greenhouses.

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