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Biological control of *Trialeurodes vaporariorum* by *Encarsia formosa* on tomato in unheated greenhouses in the high altitude tropics

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Abstract

Biological control of *Trialeurodes vaporariorum* (Westwood) by *Encarsia formosa* Gahan was tested during three consecutive production cycles (16-28 weeks) on a beef tomato (*Solanum lycopersicum* L.) crop in a glasshouse and a plastic greenhouse on the Bogota Plateau in Colombia. During the course of this study over the period 1997-1999, the mean temperature was around 16 °C in the plastic greenhouse and around 17 °C in the glasshouse. *E. formosa* was introduced at a rate of 3 adults per m^2 per week in the 1997 production cycle, and at a rate of 3 and 5 pupae per m^2 per week in 1998 and 1999, respectively. In 1997, the adult whitefly population increased exponentially to a peak of 76 adults per plant in the plastic greenhouse, while the whitefly population in the glasshouse reached a peak of only 12 adults per plant. The percentage parasitism fluctuated between 42 and 82% in the glasshouse and between 28 and 47% in the plastic greenhouse. In 1998, the *T. vaporariorum* population could not be brought under control in both greenhouses and reached a peak of 80 and 53 *T. vaporariorum* adults per plant in the plastic greenhouse and the glasshouse, respectively. Parasitism fluctuated between 55 and 97% in the glasshouse and between 32 and 84% in the plastic greenhouse. In 1999, biological control was successful in both greenhouses. Most of the time, populations of *T. vaporariorum* were lower than 1.2 adults per plant and parasitism by *E. formosa* was 80% or higher. We suggest that the higher temperature is the main reason for better parasitism in the glasshouse when compared to the plastic greenhouse. The successful results of 1999 show that biological control is possible under the short day and low temperature conditions of greenhouses situated in the high altitude tropics such as the Bogota Plateau. Recommendations are given for the application of *E. formosa* based on the results of these experiments.

Key words: greenhouse, tomatoes, biological control, *Trialeurodes vaporariorum*, *Encarsia formosa*, high altitude tropics.

Introduction

The protected cultivation of tomatoes is a recent development in Colombia, generally replacing field-grown tomatoes. The high risk due to pests and diseases, in some cases causing total loss of the crop in the field, is one of the reasons that induced the change to greenhouse production. The use of greenhouses reduces pest and disease risks, and increases production and profits. Greenhouses are currently used for tomato production in the intermediate climate zone (altitude 1800-2000 m) where traditionally field-grown tomatoes are cultivated, but also in cold climate zones such as the Bogota Plateau (altitude 2665 m). One of the particular advantages of tomato production on the Bogota Plateau is the generally reduced pest spectrum. From 1995 on, greenhouse tomatoes have been produced at the Horticultural Research Centre of the University of Bogota Jorge Tadeo Lozano, where the most important pest has been the greenhouse whitefly *Trialeurodes vaporariorum* (Westwood). Leafminers and aphids were generally kept at low densities by naturally occurring parasitoids (De Vis and van Lenteren, 1999).

Biological control of pests on greenhouse grown tomatoes has become a common practice in a number of countries (van Lenteren and Woets, 1988; van Lenteren, 1992; 1995; 2000). The parasitoid *Encarsia formosa* Gahan is traditionally used for biological control of greenhouse whitefly (van Lenteren, 1992; 1995). In Europe, *E. formosa* has also been complemented with the predator *Macrolophus caliginosus* Wagner and the parasitoids *Eretmocerus eremicus* Rose et Zolnerowich and *Eretmocerus mundus* Mercet for control of whiteflies (van Lenteren, 2000; Ardeh *et al.*, 2005). A model of the tritrophic tomato-*T. vaporariorum*-*E. formosa* system in greenhouses showed that biological control does not work under certain conditions; for example, control is not achieved when the quality of the host plants for *T. vaporariorum* is high, and when temperature conditions are unsuitable (van Lenteren *et al.*, 1996). These are exactly the conditions found in crops of beef tomatoes in unheated greenhouses in the high altitude tropics such as the Bogota Plateau: high host plant quality and unsuitable temperature conditions. Only few studies have been done on tomatoes under these conditions: Christochowitz *et al.* (1981), Hulspas-Jordaan *et al.* (1987), van Es (1982), van der Laan *et al.* (1982) and van Lenteren and Hulspas-Jordaan (1985). Studies by van Es (1982) have shown that the greenhouse whitefly population develops better on beef tomato than on round tomato varieties. Whitefly fecundity increased by a factor of 2 or more and adult longevity by a factor of 1.5-1.9 on beef tomato varieties when compared to a round tomato cultivar (van Es, 1982). In addition, the temperature in greenhouses on the Bogota Plateau is lower than the temperature in the climatised greenhouses in Western Europe (in Colombia, mean temperatures are 15-16 °C, day temperatures are 18-22 ºC and night temperatures are 5-12 °C).

Pre-1979 data (see van Lenteren and Hulspas-Jordaan, 1985) suggested that the intrinsic rate of increase (r_m) of *E. formosa* was lower than that of *T. vaporariorum* at temperatures lower than 20 °C. However, more recent studies showed that the r_m was higher than that of *T. vaporariorum* for temperatures above 12 °C (van Lenteren and Hulspas-Jordaan, 1985). This was later confirmed by the modelling work of van Roermund *et al.* (1997). Therefore, biological control should be possible under the climatic conditions prevailing in greenhouses in the high altitude tropics of Colombia. But other factors such as the parasitoid's searching behaviour might be limited at these low temperatures. Madueke (1979) showed that *E. formosa* did not fly and showed hardly any activity at temperatures lower than 21 °C. However, Christochowitz *et al.* (1981) showed that *E. formosa* could still fly at temperatures around 17 ºC and van der Laan *et al.* (1982) showed that *E. formosa* could migrate at temperatures as low as 13 °C. But later, van Roermund and van Lenteren (1995) showed that the Dutch *E. formosa* did no longer fly at 18 °C or lower temperatures in the 1990s. This fact could seriously lower the parasitoid's dispersal over the greenhouse and prevent whitefly patches from being found and parasitized.

Greenhouse experiments in The Netherlands in the 1980s showed that *E. formosa* is able to control whitefly population in greenhouses with a relatively low temperature regime (18 °C day and 7 °C night) during winter in Holland (Hulspas-Jordaan *et al.*, 1987), when day length is shorter and solar radiation lower than in Colombian greenhouses. But these conditions last only a few months at the beginning of the year in The Netherlands, while unheated greenhouses on the Bogota Plateau have a constant low mean temperature during the whole year. Therefore, the success of *E. formosa* as biological control agent of *T. vaporariorum* could not easily be predicted when growing beef tomatoes in greenhouses situated on the Bogota Plateau. However, evaluation of the potential growth of *T. vaporariorum* under the local greenhouse conditions and on the beef tomato variety Boris showed that biological control by *E. formosa* might be possible (De Vis and van Lenteren, 2002). In this paper, we evaluate the development of the *T. vaporariorum* population in the presence of *E. formosa* at greenhouse conditions on the Bogota Plateau and on a high quality tomato cultivar for *T. vaporariorum*. We will also formulate recommendations for the use of *E. formosa* based on the results of this 3-year study.

Materials and methods

Experimental greenhouses

Three tomato production cycles were conducted at the Horticultural Research Centre (CIAA) of the Jorge Tadeo Lozano University, 20 km north of Bogota at 2665 metres altitude in two types of unheated greenhouses. The first was a plastic greenhouse of the standard Colombian design (fixed open ridge and manual wall curtains) equipped with a thermal screen. The second was a "Dutch-Venlo" type glasshouse with automated roof ventilation, a thermal screen (except in 1997) and was controlled by a climate computer (Midi-Clima, Van Vliet, The Netherlands). This computer also recorded temperature in both greenhouses using NTC temperature sensors installed in a ventilated box. Relative humidity was calculated using the temperature data of a dry and a wet sensor installed in the same box. The boxes were installed in the centre of each greenhouse at plant height and every ten minutes the mean value of the temperature sensors of the previous 10 minutes were stored. Tomato plants of the variety Boris (Bruinsma Seeds, 's Gravenzande, The Netherlands) were transplanted in both greenhouses during three consecutive production cycles: 1) 6-week old plants were transplanted on May 23, 1997 and the crop was finished on January 15, 1998; 2) 7-week old plants were transplanted on May 22, 1998 and the crop was finished on January 8, 1999; and 3) 10-week old plants were transplanted on January 25, 1999 and the crop was finished on August 12, 1999. Each production cycle, a total of 1152 plants (12 beds of two rows of 48 plants each) on an area of 510 m^2 (25 m by 20.4 m) were planted in the plastic greenhouse. In the glasshouse, 1008 and 672 plants (9 and 6 beds of two rows of 56 plants each) were planted on an area of 364 and 273m^2 (28 by 13 and 9.6 m) during the first and the two last experiments, respectively. At the beginning of the experiments, when the first *E. formosa* were introduced, the plants were 10 weeks old (4 weeks after transplant) in 1997, 14 weeks old (7 weeks after transplant) in 1998 and 11 weeks old (1 week after transplant) in 1999. At that moment, a natural infestation of *T. vaporariorum* adults was already present in all experimental greenhouses. These adults may have survived from previous crops. No important immigration of *T. vaporariorum* adults could have taken place at that time as the outside climate conditions on the Bogota plateau are too cold for *T. vaporariorum* population build-up. In adjacent greenhouses, either *T. vaporariorum* was controlled chemically to low densities, or the crops in those greenhouse were not suitable for *T. vaporariorum* development.

Parasitoid release rates

E. formosa was introduced at a rate of 3 adults per m^2 per week and during 22 weeks in the 1997 trial, 3 pupae per m2 per week during 22 weeks in the 1998 trial, and 5 pupae per m^2 per week and during 13 weeks in the 1999 trial. A cumulative total of 65-66 parasitoids per m^2 of greenhouse was introduced in all the trials. In the first experiment, newly hatched parasitoids were introduced in the late afternoon (4.30 – 5.30 p.m.), while for the other two experiments, pieces of leaflets with about 70 black parasitized *T. vaporariorum* pupae were equally distributed over the greenhouses. They were fastened to the base of the lower leaves of the tomato plants. Mean emergence of the introduced pupae was 95% or higher. Parasitoids originated from the CIAA´s rearing unit, where they were reared on *T. vaporariorum* on tomato plants.

Adult whitefly and parasitism monitoring

Whitefly adults were counted weekly on the 8 upper leaves of a stratified sample of 10% of the plants: within a row, of every ten consecutive plants, one plant was

selected at random. Eggenkamp-Rotteveel Mansveld *et al*. (1978) found that a stratified random sampling alone was not suitable to reliably estimate the total whitefly population in a large greenhouse. Therefore, a census of the adult whiteflies on all plants was done every five weeks. Mean and standard error of the mean were calculated for every sampling or census day.

To visualise the spatial distribution, greenhouses were divided in plots of 4 (2x2) plants and the mean number of whiteflies per plant of the plot was calculated. According to four density classes, two-dimensional maps were constructed.

Parasitism was assessed by weekly sampling of the parasitized and non-parasitized pupae on a stratified random sample of 10% of the plants, one leaf per plant was sampled. Sampling was done on a leaf in the leaf layer where black pupae were hatching. On those leaves most of the non-parasitized pupae had already hatched. The number of parasitized pupae that were not yet black and thus counted as non-parasitized pupae was in this way reduced to a minimum. Sampling of week n+1 was done on leaves that were located 2 to 3 leaves higher on the plant than the sampled leaves of week n. Percent parasitism was calculated as the sum of the parasitized pupae found on all plants on an sampling date divided by the total number of pupae. In 1997, the measurements of parasitism were finished in the plastic greenhouse in week 20 because the population escaped biological control and chemical control was necessary. The labour-intensive measurements of parasitism were therefore suspended.

Results

The mean temperature varied among production cycles and greenhouses (figure 1A). The mean temperature in the glasshouse was always 1 to 1.5 °C higher than in the plastic greenhouse. The temperature was lowest during the 1997 trial and highest during the 1998 trial. The mean relative humidity was equal among the three trials in the plastic greenhouse, where it was higher than in the glasshouse. In the glasshouse, the relative humidity was higher during the first two production cycles than in the last one (figure 1B). The mean daily temperature curve of both greenhouses showed a small but consistent difference. Mean hourly night temperatures were between 10 and 15 ºC and day temperatures between 15 and 25 °C for both greenhouses (figure 1C, showing the data of 1998).

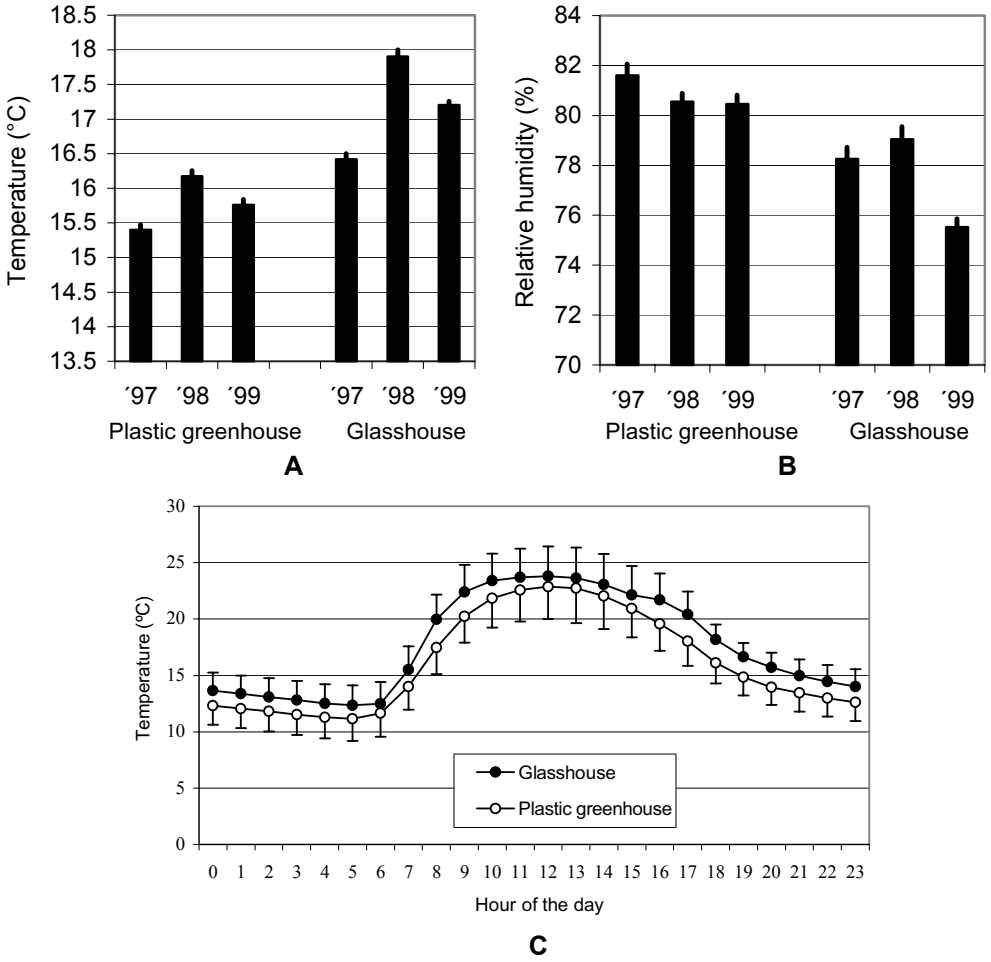

Figure 1. Mean temperature (A) and relative humidity (B) of the greenhouses during the three production cycles. Diurnal temperature regime of both greenhouses during the 1998 production cycle (C). The error bars represent the standard error of the mean with days as replicates in A and B and with mean hourly temperature of the day as replicates in C.

Powdery mildew and the diseases caused by *Botrytis* and *Alternaria* were controlled with fungicides compatible with *E. formosa* (fenarimol, diclofluanid, iprodione). Leafminers and aphids were kept at low densities by naturally occurring parasitoids during the three production cycles. The tomato russet mite, *Aculops lycopersici* (Massee), appeared at the beginning of the 1997 trial and was controlled mainly by application of the acaricides propargite, tetradifon, amitraz and hexythiazox on affected plants. Control was not very effective and by week 22 after transplant an application with propargite and tetradifon to the whole greenhouse was necessary. The mite appeared again during the 1998 experiment, in week 2 after transplant, when tetradifon and hexythiazox were applied. This could not prevent it from becoming a serious pest and 4-6 applications with fenbutatinoxide had to be applied on the whole crop and throughout the production cycle. After this production cycle, the greenhouse was disinfected with bleach solution to eradicate the mites and during the first two weeks of the 1999 production cycle fenbutatinoxide was applied preventively twice to the new plants and greenhouse structures. The pest did not reappear during the rest of this production cycle. The total number of pesticide applications on the whole crop was 3 in 1997, 6-7 in 1998 and 3-4 in 1999.

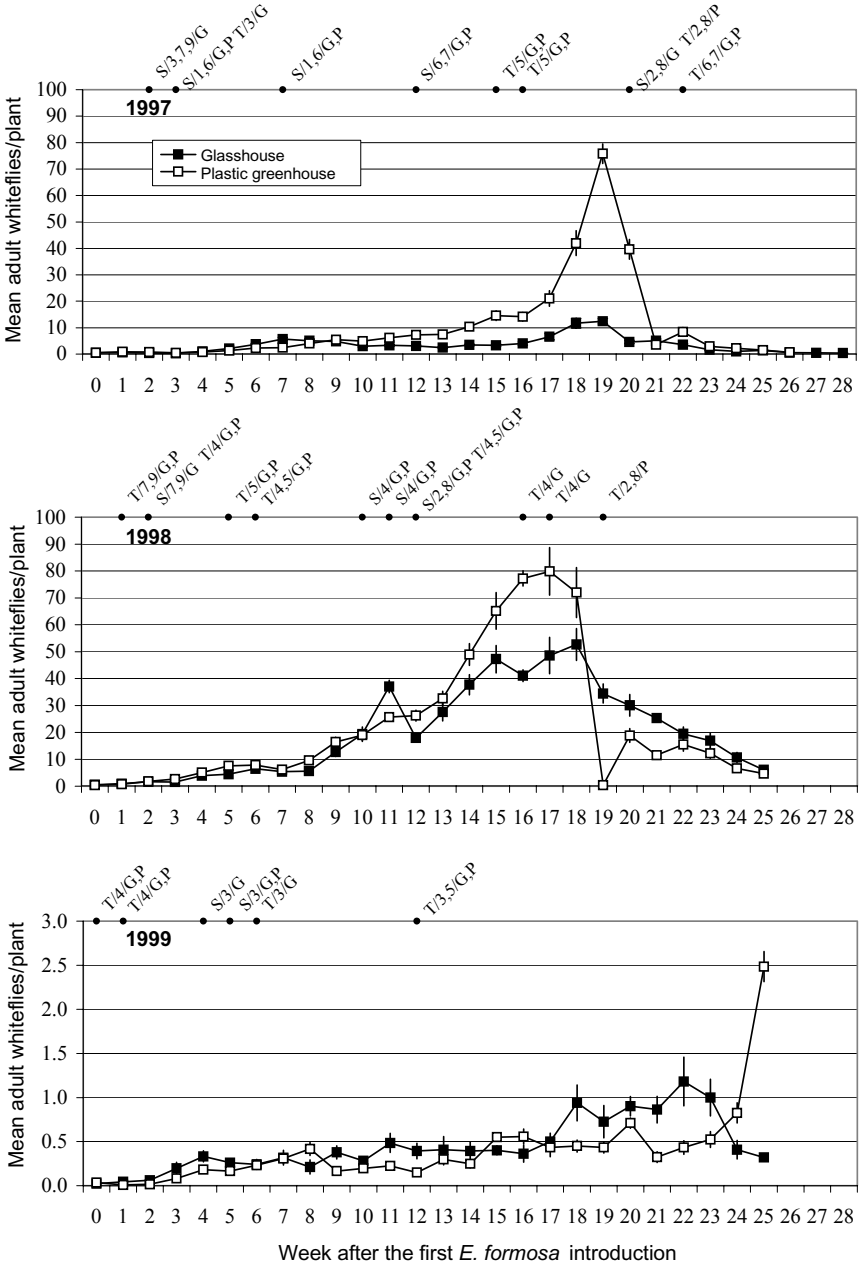

Figure 2. Mean number of adult whiteflies per plant in the glasshouse and in the plastic greenhouse during the three consecutive production cycles. The chemical treatments are specified above the graphs: S=spot treatment; T=total crop treatment; G=glasshouse; P=plastic; 1=amitraz; 2=buprofezin; 3=fenarimol; 4=fenbutatinoxide; 5=iprodione; 6=propargite; 7=tetradifon; 8=thiocyclam hydrogen oxalate; 9=hexythiazox. The error bars represent the standard error of the mean.

At the start of the experiments, the whitefly population was similar in 1997 and 1998, but significantly lower in 1999: 0.47 and 0.57 whitefly adults per plant in the glasshouse and the plastic greenhouse respectively in 1997, compared to 0.51 and 0.42 in 1998 and 0.023 and 0.034 in 1999.

In 1997, from week 3 on, the population started to increase in both greenhouses (figure 2), but at a higher rate in the glasshouse compared to the plastic greenhouse. In week 7, the population reached a first peak in the glasshouse after which it decreased and became stable at a level of about 3 whiteflies per plant. In the plastic greenhouse, however, the population increase slowed down only slightly at that time. Between week 10 and 16, parasitism was near 80% in the glasshouse compared to about 40% in the plastic greenhouse (figure 3). As of week 16, the *T. vaporariorum* populations started to grow faster again in both greenhouses until reaching a peak in week 19. This increase coincided with a decrease in the parasitism in both greenhouses. In week 20, plants with more than 100 whitefly adults were sprayed with buprofezin and thiociclam, after which the whitefly population declined in both greenhouses. Only 2.8% of the plants were spot sprayed in the glasshouse, but in the plastic greenhouse the infestation was so high that all plants had to be sprayed.

Parasitism continued declining during the rest of the production cycle. The total number of black and white pupae per sampled leaf increased exponentially to a maximum of 34 in the plastic greenhouse in week 19. At that time, a mean of 9 pupae per leaf was found in the glasshouse and the maximum for the glasshouse of 12.1

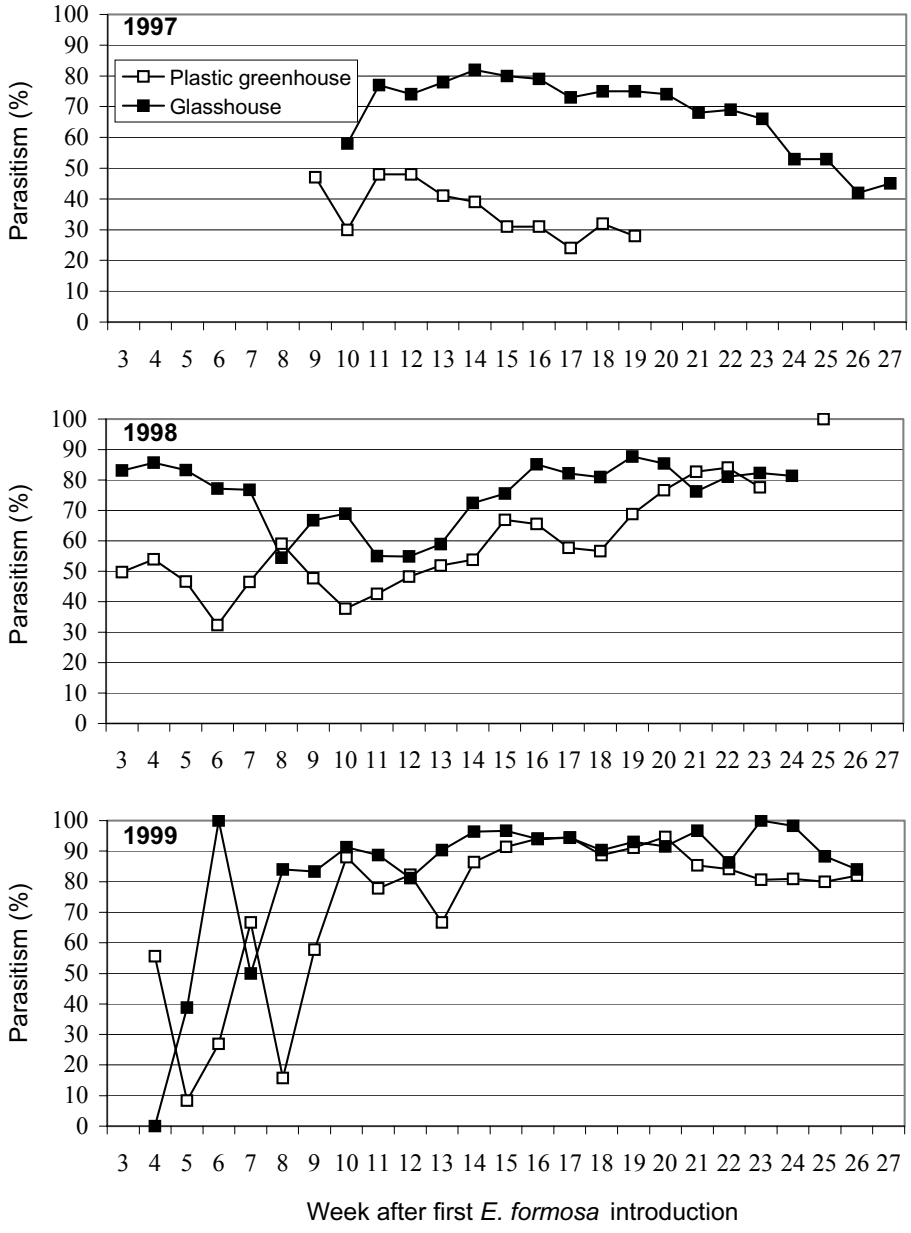

Figure 3. Percent parasitism in the plastic greenhouse and in the glasshouse during the three consecutive production cycles.

pupae per leaf was found in week 22. The number of pupae per leaf was always higher in the plastic greenhouse (figure 4).

In 1998, the *T. vaporariorum* adult population increased faster than in 1997 in both greenhouses. In the glasshouse, it surpassed that of the plastic greenhouse in week 11 (figure 2). In week 12, plants with more than 100 adults were sprayed with buprofezin and thiociclam: 22% of the plants in the glasshouse were sprayed compared to 5% in the plastic greenhouse. This caused an important decline in the *T. vaporariorum* adult population of the glasshouse, but not in the plastic greenhouse. Parasitism in the glasshouse, which had been below 80% during the previous five weeks, increased again to 80% by week 16 (figure 3). During weeks 15-18 the population of *T. vaporariorum* adults did not increase very much in the glasshouse and reached a maximum of 53 adults per plant by week 18. At that point, the population had already reached 80 adults per plant in the plastic greenhouse. Because of the high percentage parasitism (more than 80%) and the stable number of whiteflies, the glasshouse was not sprayed in week 19. The plastic greenhouse, however, was sprayed completely with buprofezin and thiociclam because of the lower level of parasitism (60%) and the higher adult whitefly population. Parasitism remained below 60% in the plastic greenhouse most of the time, but after the chemical control it increased gradually to more than 80% by week 21. The whitefly population remained below 20 adults per plant. In 1998, the population peaked

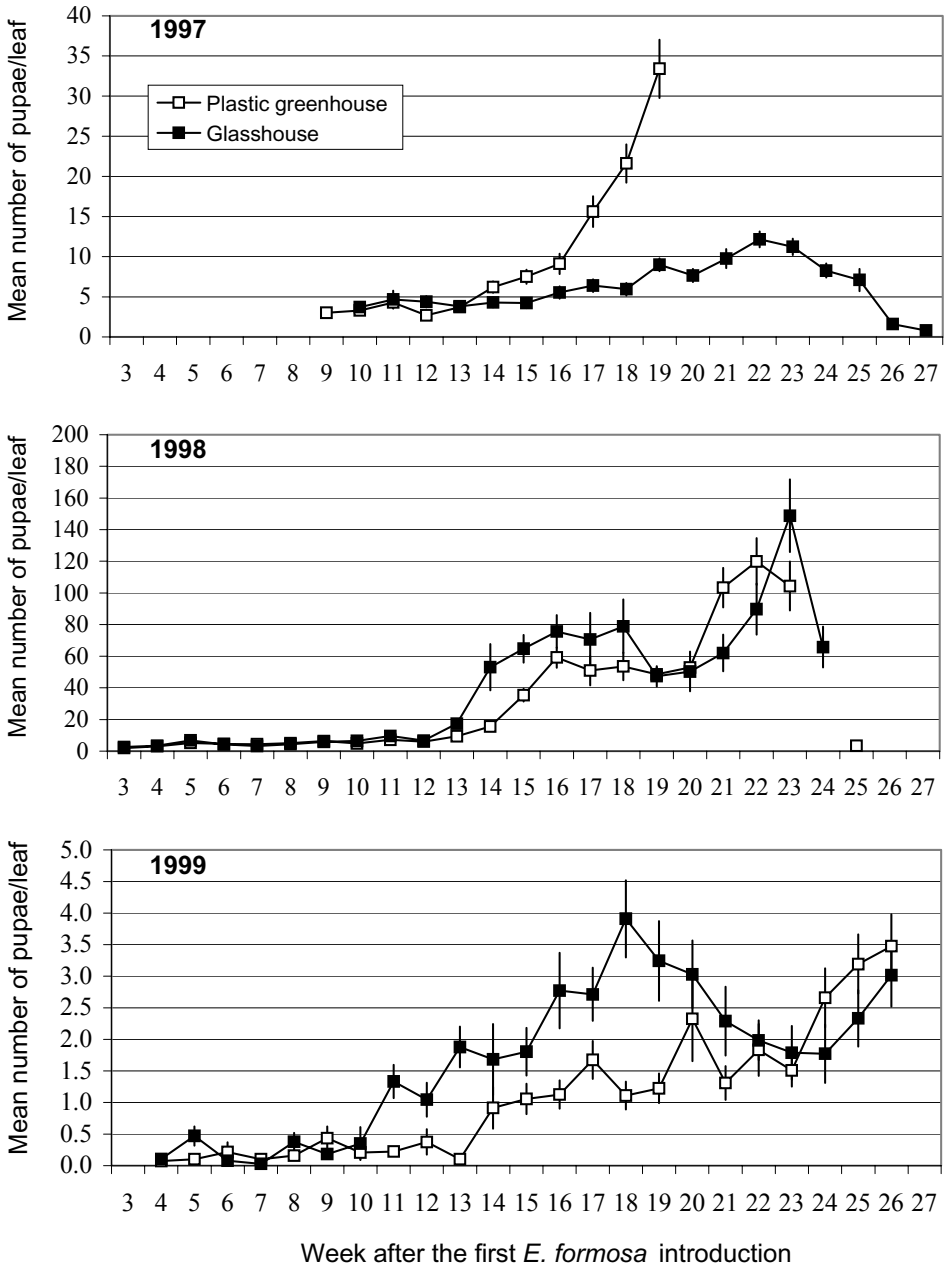

Figure 4. Mean total number of pupae (black+white) per leaf in the plastic greenhouse and in the glasshouse during the three production cycles. The error bars represent the standard error of the mean.

3 weeks earlier than in 1997. Also the number of pupae per leaf increased earlier in 1998. In 1997, the total number of black and white pupae in the plastic greenhouse was 35 in week 19, while this level was already reached by week 15 in 1998. By week 15, more than 60 pupae per leaf were found in the glasshouse. In 1998, the number of pupae per leaf was almost always higher in the glasshouse than in the plastic greenhouse and also higher than the number of pupae per leaf found in both greenhouses in 1997 (figure 4).

In 1999, the population of whiteflies was very low during the whole cycle and did not pass 1.2 adults per plant in the glasshouse and 2.5 adults per plant in the plastic greenhouse. At the end of this production cycle, the adult population was increasing in the plastic greenhouse, while in the glasshouse it was decreasing (figure 2). Parasitism was above 80% in both greenhouses, but this level was attained more quickly in the glasshouse (week 6) than in the plastic greenhouse (week 10). It was almost always higher in the glasshouse than in the plastic greenhouse (figure 3). The total number of black and white pupae per leaf was very low in comparison with the previous experiments and was higher in the glasshouse than in the plastic greenhouse most of the time (figure 4).

The distribution maps of the 1997 experiment (figures 5 and 6) show that the initial whitefly population had a

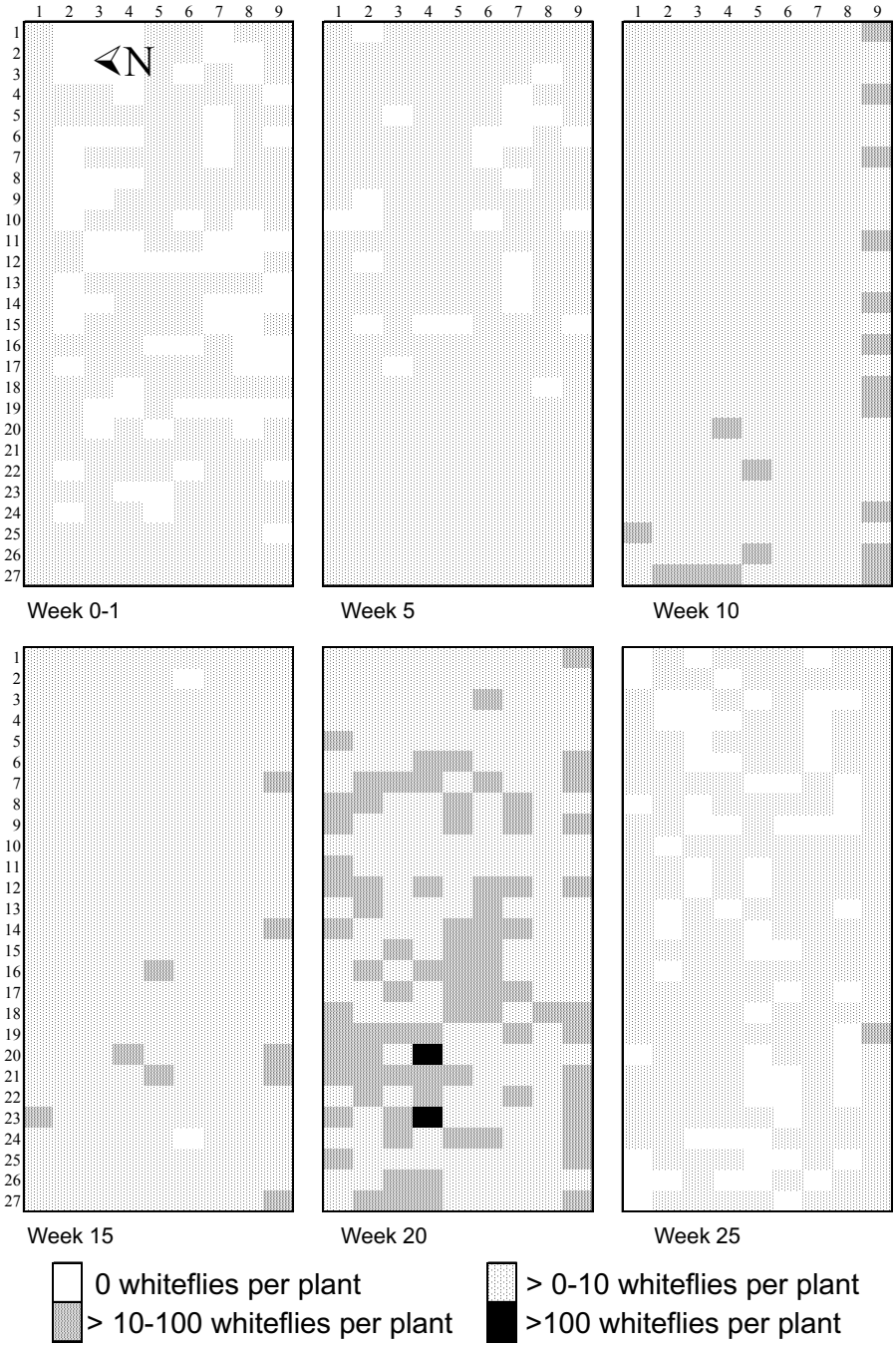

Figure 5. Spatial distribution of adult whiteflies in the 1997 glasshouse trial. Each square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction.

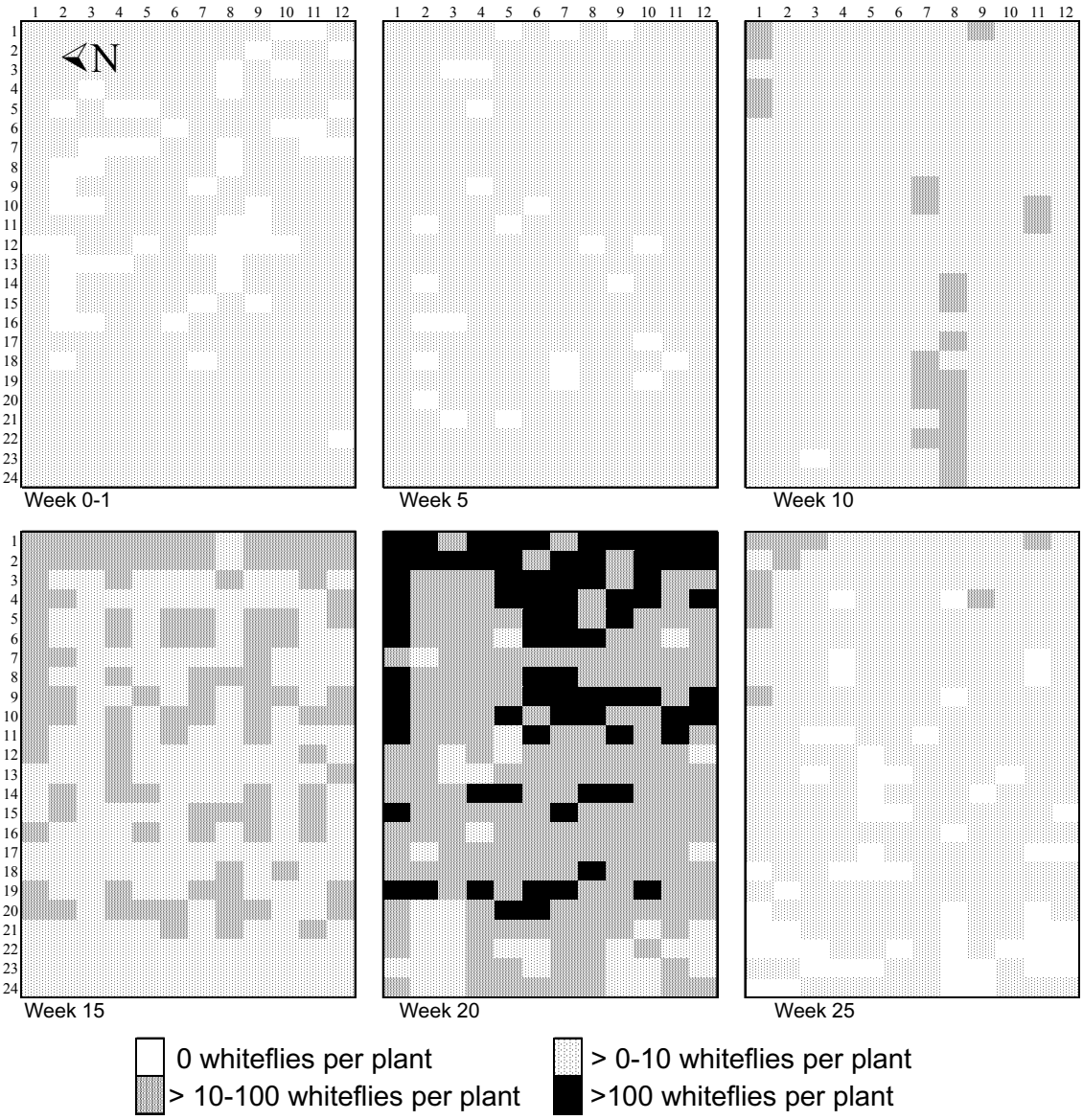

Figure 6. Spatial distribution of adult whiteflies during the 1997 plastic greenhouse trial. Each square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction.

rather random distribution. For the first three sampling dates, no significant differences can be distinguished between the two greenhouses. In both greenhouses, more uninfested plots were observed at the first sampling (week 1-2). These gradually disappeared and by week 10 all plots were infested and the first plots with a mean of more than 10 adult whiteflies per plant appeared. In the plastic greenhouse, a considerable increase in adults could be observed in the eastern part of the greenhouse when comparing the maps of weeks 10 and 15. By week 20, many plots with a mean of more than 100 whiteflies appear in that greenhouse, while in the glasshouse only two plots with a mean of more than 100 whiteflies were found. Following the chemical control of week 20, the population declined and the whitefly density and distribution of week 25 was similar to that of weeks 1-2, but in the plastic greenhouse a slightly higher population was found in the northeast corner. In both greenhouses, the initial random distribution developed to a more aggregated distribution. Patches separated by whitefly free zones did not develop, although plants without whiteflies were frequently observed alongside plants that were heavily infested. In 1998, (figures 7 and 8) and 1999 (figure 9 and 10), the distribution was similar to that of 1997 in both greenhouses, but with higher levels in 1998 and lower levels in 1999. The whitefly population was always higher along the southern edge of the glasshouse and the eastern edge of the plastic greenhouse. In 1998, the initial whitefly population was higher and this led to a faster complete infestation, attained in week 6, compared to week 10 in 1997. Moreover, the first plots with more than 100 adult whiteflies appeared in week 6 (glasshouse) or 11 (plastic greenhouse), compared to week 20 (both greenhouses) in 1997. Figures 9 and 10 show the low initial infestation in 1999 and during the

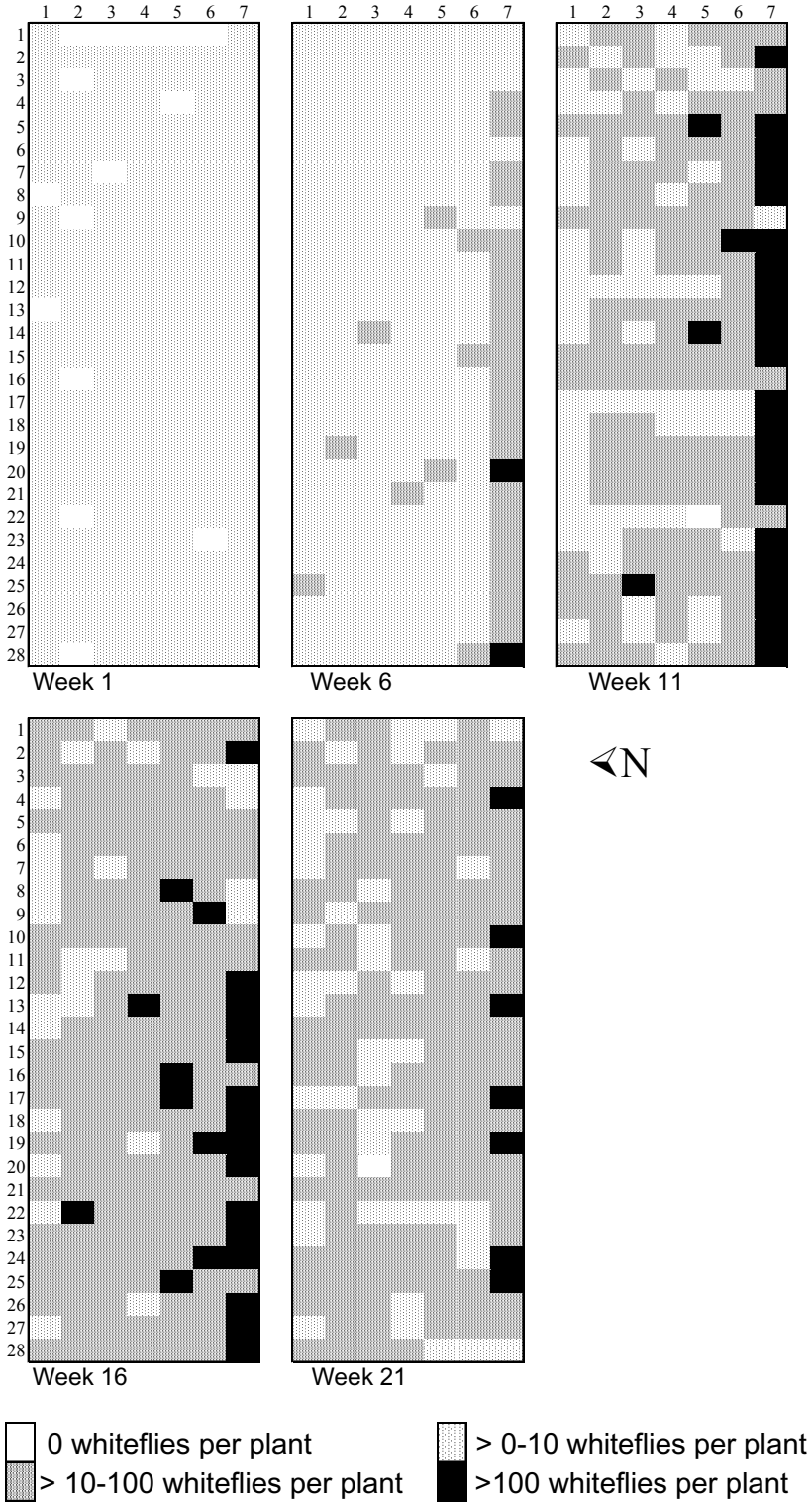

Figure 7. Spatial distribution of adult whiteflies in the glasshouse during the 1998 trial. Every square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction.

whole production cycle many plots free of adult whitefly were found. During that year no plot with a mean of more than 100 adult whiteflies per plant appeared and only few with more than 10 adult whiteflies per plant.

Discussion

All the experiments were successful during the first 16 production weeks, but afterwards *T. vaporariorum* population escaped control in the first two trials. The experiments lasted between 26 and 32 weeks, covering 3.6

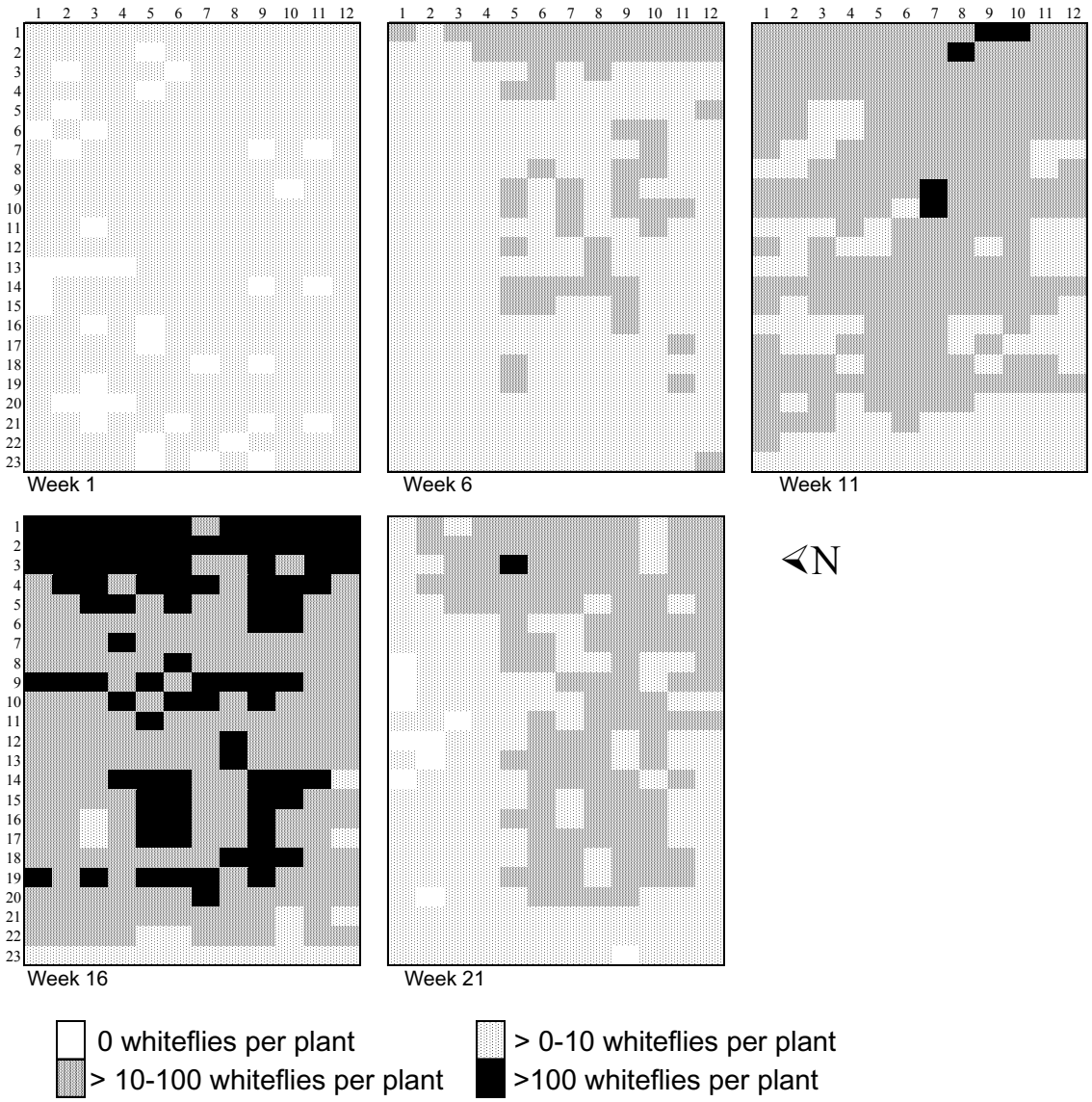

Figure 8. Spatial distribution of adult whiteflies in the plastic greenhouse during the 1998 trial. Every square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction.

to 4.7 whitefly generations, which is similar to the current duration of commercial tomato crops in Colombia. The experiments of Hulspas-Jordaan *et al.* (1987), covered a period of 18 weeks, corresponding to about 2 whitefly generations and those of Eggenkamp-Rotteveel Mansveld *et al.* (1982) covered 16 weeks, corresponding to about 2.9 generations. These authors concluded that biological control was successful. However, their experiment did not cover the normal commercial production cycle of almost one year. In order to be able to conclude if biological control is efficient, greenhouse experiments should therefore cover the total length of the commercial crop cycle.

In the previous mentioned greenhouse experiments no data on adult whitefly or parasitoid populations per plant were shown. The results for the percentage parasitism of Hulspas-Jordaan *et al.* (1987) and those of Eggenkamp-Rotteveel Mansveld *et al.* (1982) are similar to those we found for the glasshouse in 1997 but higher than those we found in the plastic greenhouse. Also the total number of pupae per leaf we measured in the glasshouse is similar to the number we calculated with the data of Hulspas-Jordaan *et al.* (1987). They measured the total number of new empty white and new full black pupae that appeared in the crop, reaching a maximum of 2800 pupae in week 12 of their experiment. Based on the estimated temperature of 13.1 °C, the estimated leaf initiation rate of 1.5 leaves per week (Jones *et al*., 1991) and the number of plants (175) this would result in 10.7 pupae per leaf for their experiment. We found a maximum of 12.1 pupae per leaf in the 1997 glasshouse experiment. In the plastic greenhouse, however, the mean number of pupae per leaf was higher as compared to both our results of the glasshouse and those of Hulspas-Jordaan *et al.* (1987). Several factors could have influenced this result:

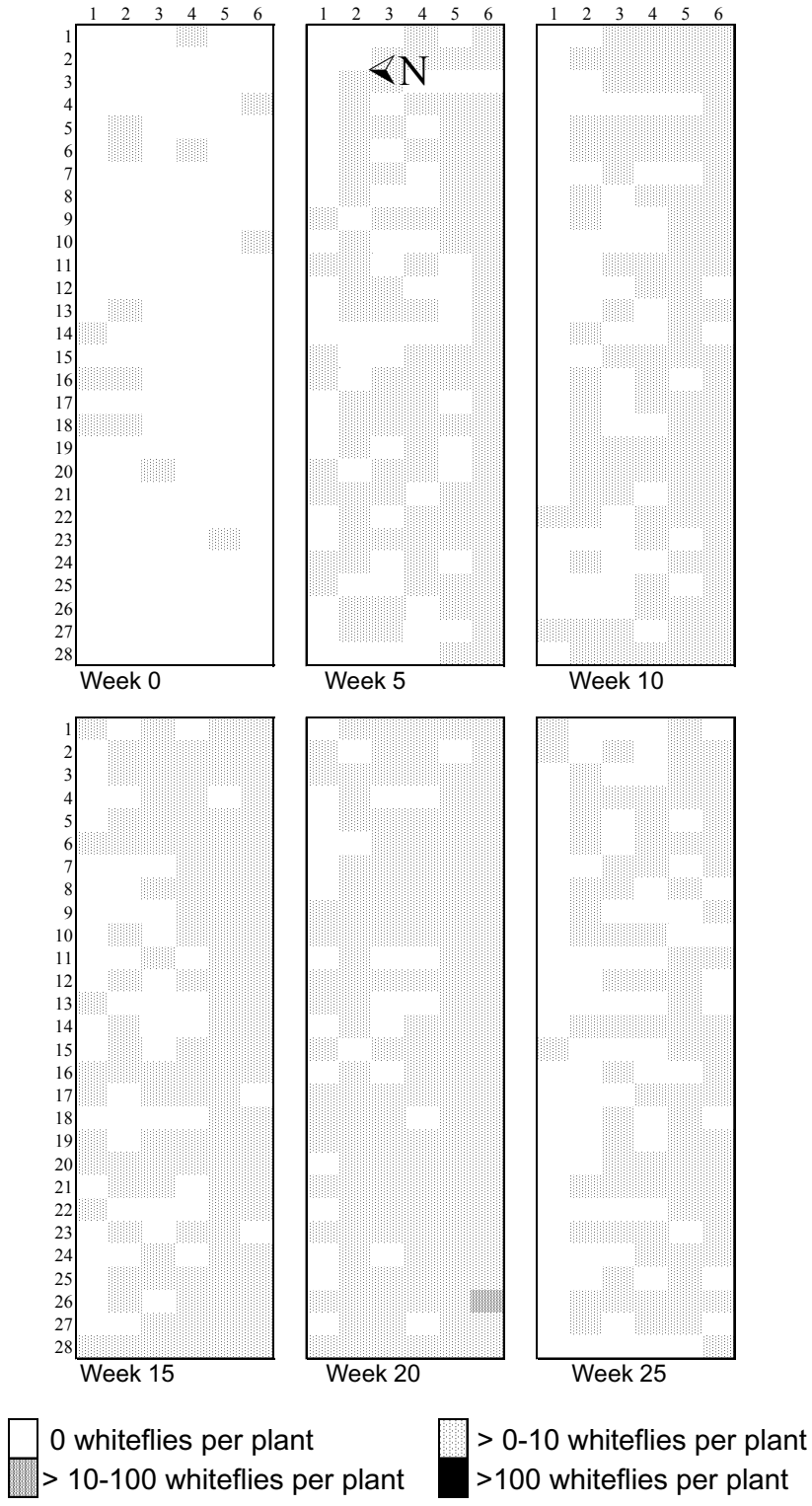

Figure 9. Spatial distribution of adult whiteflies in the glasshouse during the 1999 trial. Every square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction.

Temperature

The small but continuous higher temperature in the glasshouse (figure 1A and 1C) created a higher advantage of *E. formosa* over *T. vaporariorum* in the glasshouse than in the plastic greenhouse. With increasing temperature, the increase in fecundity, oviposition frequency and the decrease of immature development and pre-oviposition period (in the range of 15-25 °C) is higher for *E. formosa* than for *T. vaporariorum* (van Roermund and van Lenteren, 1992a; 1992b). The threshold temperatures for egg maturation and immature development of *E. formosa* and *T. vaporariorum* are

14.4 ºC and 7.5 ºC respectively (van Roermund and van Lenteren, 1992a; 1992b). More hours below the *E. formosa* threshold were accumulated during the trial in the plastic greenhouse than in the glasshouse. Additionally, searching efficiency parameters such as walking speed and walking activity of *E. formosa* increase with increasing temperature (van Roermund and van Lenteren, 1995). This may lead to more encounters and parasitism in the glasshouse.

The exact mean daily temperature of the experiment of Hulspas-Jordaan *et al.* (1987) is not given in their paper, but they used a temperature set point at their temperature regulation system of 18 ºC during the day and 7 ºC at night. We calculated that this would lead, depending on the day length, to a mean day temperature of 11.6 ºC at the beginning and 13.1 ºC at the end of the experiment. This is much lower than the temperature in our plastic greenhouse. If they had successful biological control under those conditions, we would expect successful control in our plastic greenhouse. However, in our experiment the night temperature was in most cases between the threshold temperatures of *E. formosa* (11.4 ºC) and *T. vaporariorum* (7.5 ºC) (van Roermund and van Lenteren, 1992a; 1992b), while in the experiment of Hulspas-Jordaan *et al*. (1987), the night temperature was below the threshold for both insects. The experiment of Hulspas-Jordaan *et al.* (1987) can therefore be considered as an experiment that was done at 18 ºC with intermittent zero development periods at 7 ºC. Under these conditions, *E. formosa* has a clear advantage over *T. vaporariorum*. During the experiment of Eggenkamp-Rotteveel Mansveld *et al.* (1982), the mean temperature increased from 14.2-15.7 °C in week 1 to 18.6-22.1 °C in week 16, with maximum tempera-

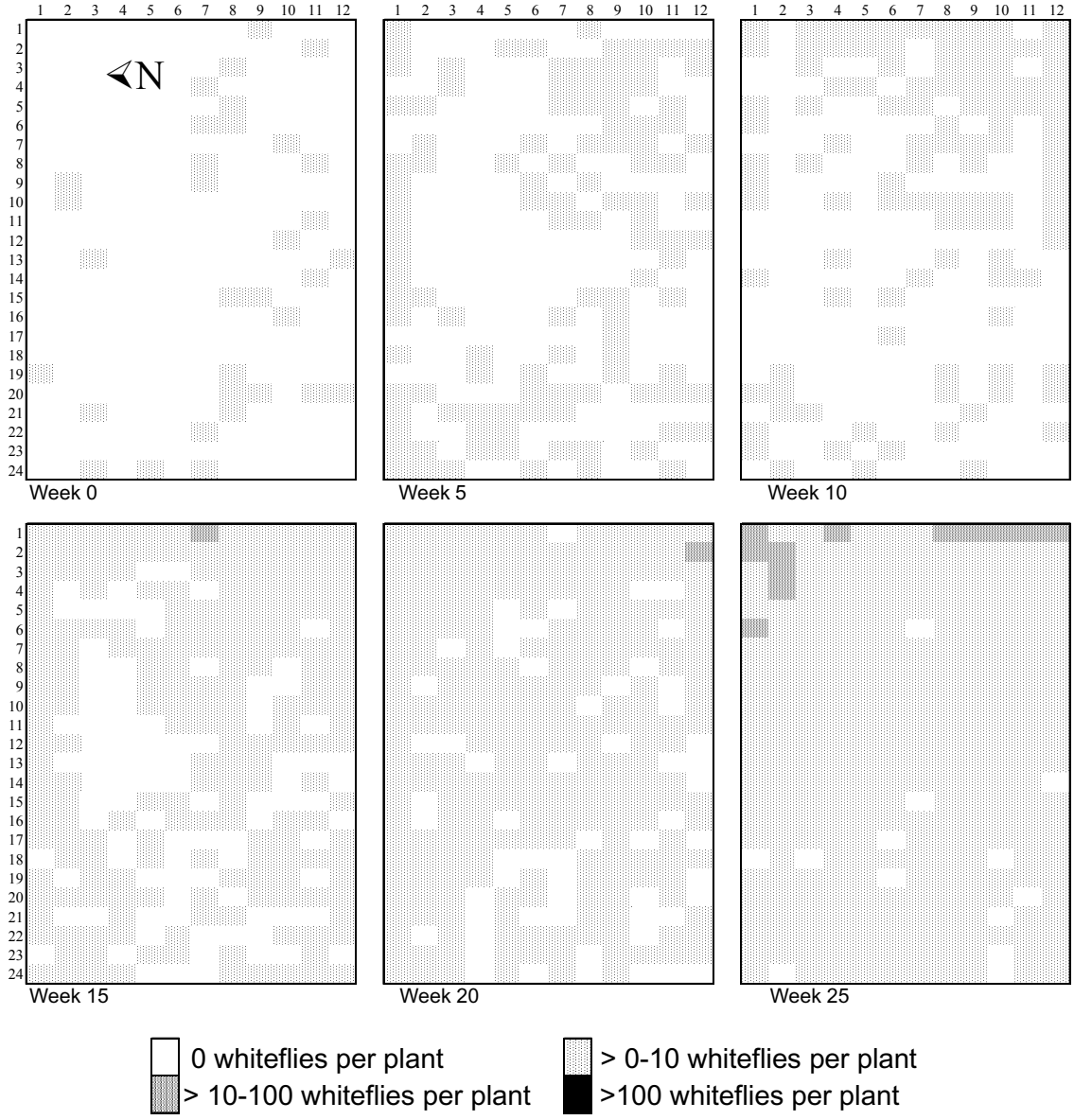

Figure 10. Spatial distribution of adult whiteflies in the plastic greenhouse during the 1999 trial. Every square represents four plants and the grey scale indicates the mean number of whitefly adults on the 8 upper leaves of the four plants. The week number indicates the number of weeks after the first *E. formosa* introduction

tures of more than 25 °C during all the weeks. So in this experiment, the temperature conditions were also more favourable than in our experiments.

Based on the previous considerations, a better temperature management in the plastic greenhouse could possibly increase the biological control to the same level as in the glasshouse. In 1998, a higher temperature was attained by managing the greenhouse vents (figure 1). Parasitism was higher than in 1997 but still insufficient in the plastic greenhouse. In the glasshouse, it was initially higher than 80% but then decreased to a level close to that of the plastic greenhouse. It was possibly affected by pesticide applications (see further) and was insufficient for efficient biological control in both greenhouses. However, at the end of the production cycle it increased to 80% in both greenhouses, showing that a high percentage of parasitism was also possible in the plastic greenhouse. In 1999, the mean temperature in the plastic greenhouse was only 0.4 °C higher than in 1997 and parasitism increased gradually to levels reaching 80% showing that successful control in the plastic greenhouse is possible even at a mean temperature less than 16 °C. The glasshouse showed, however, during the three production cycles a better parasitism and control. The higher mean temperature of about 1.5 °C is probably the most important advantage of the glasshouse that can explain the differences in parasitism and control of the whitefly population. Based on the previous results, temperature management seems to be an important factor in the success of biological control in greenhouses on the Bogota Plateau.

Parasitoid introduction and initial whitefly infestation

In the first experiment, adults were introduced because they were easily harvested in the hatching chamber (Hulspas-Jordaan *et al.*, 1987). However one of the possible reasons of the unsuccessful control in the first experiment were possible negative effects of harvesting and managing adults (e.g. injury caused during the harvesting process) and therefore pupae (Eggenkamp-Rotteveel Mansveld *et al.*, 1982) were introduced in the following experiments.

In the first two experiments introductions started when whitefly larvae were found in the crop. Because of unsuccessful control in the first two experiments we started introducing earlier in the last experiment as to promote a higher parasitism from the beginning. Additionally, also the rate was increased. The introduction scheme of Hulspas-Jordaan *et al.* (1987) consisted of 4 introductions with a total of 20.6 *E. formosa* adults per m^2 in a period of 6 weeks (week 2 after transplant, 5.15 adults; week 4, 5.15 adults; week 6, 5.15 adults and week 8, 5.15 adults). Eggenkamp-Rotteveel Mansveld *et al.* (1982) introduced 27.5 *E. formosa* pupae per m^2 in the same 6-week period (week 4 after transplant, 2 pupae; week 6, 5.9 pupae; week 8, 12.6 pupae and week 10, 7 pupae). In our experiments, 3 *E. formosa* adults (1997) or pupae (1998) per m^2 were introduced weekly until reaching a total of 66 per m^2. During the first 6 weeks we introduced 18 *E. formosa* per m^2. As we worked with a beef tomato variety, which is a better host plant for *T. vaporariorum*, we supposed that a higher number of *E. formosa* should be introduced to obtain control. For the 1999 production cycle, we decided to introduce 5 pupae per m^2 per week, so as to reach a total of 30 after 6 weeks. This seemed to be effective as in the last experiment parasitism was much higher from the beginning but this could also be due tot the lower initial whitefly population. The initial whitefly population in the 1997 and 1998 production cycles was relatively high: between 0.42 and 0.57 adults per plant. Hulspas-Jordaan *et al*. (1987) started with 0.42 whitefly adults per plants, but Eggenkamp-Rotteveel *et al.* (1982) started with only 0.0067 adults per plant, and Woets (1978) found that the initial whitefly infestation on commercial farms reached only 0.001 to 0.01 adults per plant. Because of the lower initial introductions during the 1997 and 1998 production cycles, the relatively high initial *T. vaporariorum* infestation and the high leaf area, a lot of immature stages could have escaped parasitism at the beginning of the experiment, resulting in a low parasitism and a high adult whitefly population increase. In 1999, the disinfection of the greenhouses to control the tomato russet mite reduced the initial whitefly infestation to only 0.023-0.034 adults per plant. This, together with the higher *E. formosa* introduction rate, resulted in a much higher ratio of parasitoids per whitefly and was probably one of the most important factor of success for the biological control in both greenhouses.

Pesticide application

The *T. vaporariorum* population got out of control in both greenhouses in 1998. This was possibly caused by the sprayings against the tomato russet mite. Although in most of the cases the products were compatible with the use of parasitoids (table 1), many *E. formosa* adults were found dead after pesticide applications. We suppose that this was caused by the physical effect of applying water with high pressure to plants rather than by the chemical products themselves. We therefore propose to make additional parasitoid introductions after full crop applications with pesticides, and particularly during the introduction phase. In 1999, the biological control of *T. vaporariorum* was successful in both greenhouses. The low number of pesticide applications resulted in a less negative effect on *E. formosa*.

For successful control, follow up of hot spots is necessary and eventual chemical control in those hotspots can prevent dissemination of the whiteflies into the rest of the greenhouse where biological control is functioning well. We applied chemical control on plants with more than 100 whitefly adults but this threshold was rather high as population escaped control in the plastic greenhouse after hot spot treatments in the plastic greenhouse in 1997 and 1998. In commercial greenhouses, we would therefore recommend start hot spot treatments at lower levels.

Spatial distribution

In the plastic greenhouse, the population was always higher near the eastern wall at the end of the production cycle, although the initial population was not higher than in the rest of the greenhouse. In the glasshouse, highest populations were found near the southern wall of

Table 1. Pesticides used during the trials and their compatibility with natural enemies. The value indicates the toxicity of the respective product according the IOBC rating system. The persistence of the product, in weeks, is given between brackets.

Active ingredient	Trade name	*E. formosa* [1]		Other parasitoids used in greenhouse pest control [1]	Predators used in greenhouse pest control[1]
		Adult	Pupa		
Amitraz	Mitac	4 (2-4)	4	1, 2 (0)	1, 2, 3, 4 (0, 3)
Buprofezin	Oportune	2 (0.5)	1	1 (0)	1, 2 (1)
Fenarimol	Rubigan	1 (0)	1	1 (0)	1 (0)
Fenbutatinoxide	Torque	1 (0)	1	1 (0)	1 (0)
Hexythiazox	Nissorun	1 (0)	1	1 (0)	1 (0)
Iprodione	Rovral	1 (0)	1	1 (0)	1 (0)
Propargite	Omite	3 (1)	3	1,2,3,4 (0, ?)	1,2,3,4 (0, ?)
Tetradifon	Tedion	1 (0.5)	2	1 (0)	1,2 (0)
Thiocyclam hydrogen-oxalate	Evisect	1 (0)	4	1,2,3,4 (?)	1,2,3,4 (0, 1, 2)

[1] 1 = harmless or less than 25 % mortality; 2 = slightly harmful, between 25 and 50 % mortality; 3 = moderately harmful between 50 and 75 % mortality and 4 = very harmful, more than 75 % mortality. When more than one figure is given, toxicity for the different natural enemies was different. A question mark indicates that no data are available. Source: http//www.koppert.nl; Side effect database.

the greenhouse. In both cases, the wall consisted of a plastic division between two parts of the respective greenhouses. Possibly, the greenhouse was locally warmer, enhancing whitefly development but on the other hand a higher temperature should also enhance biological control. Parasitism near the division wall was not different from the rest of the greenhouse in the glasshouse but significantly lower in the plastic greenhouse. An other possibility is differential migration of pest and/or natural enemies: whiteflies might have migrated more than *E. formosa* to these areas. More research is, however, needed to clarify this phenomenon.

Previous studies of Eggenkamp-Rotteveel Mansveld *et al*. (1982) showed that in a large greenhouse hot spots developed, separated by whitefly-free zones. This was not the case in our experiments. Our greenhouses were, however, much smaller and initial populations were always much higher causing a general infestation after five weeks, except for the experiments in 1999, when populations were very low and 15 to 20 weeks were needed before the greenhouses were completely infested.

Recommendations

We can recommend the use of biological control of *T. vaporariorum* by *E. formosa* in unheated greenhouses with tomato on the Bogota Plateau, and based on our experiments and data from the literature, we propose the following approach for its successful implementation:

- Start a new crop with a clean greenhouse and clean plants so as to avoid population build-up at the beginning of the crop.
- Introduce *E. formosa* as pupae to avoid possible negative effects of dealing with adults which are easily injured during harvesting, transport and release.
- On host plants that have a high quality for greenhouse whitefly (e.g. beef tomato), introduce 5 pupae *E. formosa* per week and per m^2 and during 13 weeks from the first observation of *T. vaporariorum* adults.
- On low quality host plants, this dosage can possibly be reduced to 4-5 introductions of 5 pupae per m^2 at fortnightly intervals, which is commercially used in Europe (Eggenkamp-Rotteveel Mansveld *et al.,* 1982).
- Manage the ventilation in such a way that it increases greenhouse temperature.
- Avoid spraying, even with compatible products. If pesticide applications have to be made, only apply spot treatments; if full crop applications are necessary during the introduction phase, increase the parasitoid introductions to replace the killed *E. formosa* adults.

Our additional observations of the natural control of aphids and leaf miners (i.e. control without costs!) make of biological control a very attractive alternative for the local growers.

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