# Combined monitoring of pest and beneficial insects with sticky traps, as basis for decision making in greenhouse pest control - a proof of concept study

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# Contents

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# Abbreviations

| | |
|---|---|
| % | Percentage |
| ANOVA | Analysis of Variance |
| AEP | Automatische Entscheidungshilfe für den Pflanzenschutz unter Glas |
| °C | degree Celsius |
| cm, $cm^2$ | centimeter, square centimeter |
| CW | calendar week |
| d | day |
| df, $df_{num}$, $df_{den}$ | Degrees of Freedom, df (numerator), df (denominator) |
| DSS, DSSs | decision support system, decision support systems |
| EF | *Encarsia formosa* |
| EIL | economic injury level |
| ET | economic threshold |
| et al. | *et alii* (and others) |
| Exp | experimental |
| g | gram |
| GH, GH-C | greenhouse, greenhouse chamber |
| GHa, GHc | greenhouse area, greenhouse complete |
| GLM | generalized linear model |
| h | hour |
| ha | hectare |
| i.e. | *id est* (that is) |
| IPM | Integrated Pest Management |
| kg | kilogram |
| km | kilometer |
| l | liter |
| L1, L2, L3, L4 | first, second, third, fourth instar larvae or nymph |
| LM | linear model |
| ln | natural logarithm |
| m, $m^2$ | meter, square meter |
| mm | millimeter |
| MP | *Macrolophus pygmaeus* |
| N | number |
| n.a. | not applicable |
| ns | non significant |
| PR | parasitism rate |
| PSM | Pflanzenschutzmittel |
| P-T | poly-tunnel |
| $R^2$ | Coefficient of Determination |
| RH | relative humidity |
| SD, SE | standard deviation, standard error |
| sp. | species (singular) |
| TH | threshold |
| TV | *Trialeurodes vaporariorum* |
| $\chi^2$ | Chi-Square |
| YT | yellow trap |

# Summary

Integrated Pest Management (IPM) becomes more and more standard in agricultural production. This concept relies primarily on naturally occurring, modified or introduced biological control agents, and tolerates pest densities below predefined thresholds. The application of these thresholds, the selection of suitable natural enemies, the monitoring of their performance, and the need for selective insecticides accounts for the complexity of decision making in IPM. The Achilles heel for optimal decision making is a reliable and cost efficient monitoring, providing growers with area-specific information of pest and beneficial densities. Sticky trap monitoring meets these requirements, as long as correlations of trap catch with on-crop densities can be established at practice relevant densities, and hold for accurate predictions in new growing seasons. With regard to these demands, a sticky trap monitoring strategy in greenhouse tomato for control of the Greenhouse Whitefly *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae) by the natural enemies *Encarcia formosa* Gaham (Hymenoptera: Aphelinidae) and *Macrolophus pygmaeus* Rambur (Hemiptera: Miridae) is evaluated in this study.

In Chapter 1 it is shown that a single yellow sticky trap provides reliable information on *T. vaporariorum* nymphal density on an area of at least 170 m². Correlations differed for specific developmental stages, i.e. adults < nymphs < nymphs (previous week). Increasing trap catches of the parasitoid *E. formosa* indicated high parasitism, with ≥ 6 parasitoids / trap as suitable threshold for established biological control. Because no information about the attraction of the predatory bug *M. pygmaeus* was available from literature, its response to the most widely applied sticky trap types, i.e. blue and yellow traps, was tested in Chapter 2. The results indicate that *M. pygmaeus* is moderately and indifferently attracted to both colours. Adults caught on yellow and blue traps were correlated with the population densities on the crop in a greenhouse experiment, but more *M. pygmaeus* were trapped on blue compared to yellow sticky traps. However, due to the known preference of *T. vaporariorum,* yellow traps are recommended for a combined pest-predator monitoring. In Chapter 3, the yellow trap monitoring of all three insects was validated for greenhouses and greenhouse areas, by application of the established correlations during a full new growing season. Prediction accuracy for damaging levels was accurate for *T. vaporariorum* nymphs, but could not be validated for adults, because the prediction never exceeded the tentative damaging level. Population peaks were strongly underestimated for both whitefly stages, indicating that a conservative threshold should be applied to secure timely detection of critical pest densities. Determination of established biological control was accurate for both natural enemies, but only high parasitism rates of *E. formosa* were accurately predicted, whereas population development of *M. pygmaeus* was accurately predicted at all times. The potential of economic savings for monitoring driven beneficial introductions is shown. Based on these results, the concept and realization of an area specific Decision Support System (DSS) for optimal use of beneficials is presented in Chapter 4.

**Key words:** Sticky Trap, Monitoring, Decision Support System,

*Trialeurodes vaporariorum*, *Encarsia formosa*, *Macrolophus pygmaeus*

# Zusammenfassung

Der integrierte Pflanzenschutz wird immer mehr zum Standard in der Pflanzenproduktion. Dieses Konzept basiert auf einer natürlichen Regulierung der Schädlingsdichte, wobei eine aktive Bekämpfung erst nach Überschreitung festgelegter Schadschwellen und in erster Linie durch den Einsatz natürlicher Gegenspieler erfolgt. Das Anwenden von Schadschwellen, die Auswahl geeigneter Nützlinge und die Überwachung ihrer Aktivität, sowie die Anwendung Nützlingsschonender Pflanzenschutzmittel macht die Entscheidungsfindung komplex. Der Schlüssel für optimale Schädlingsbekämpfung ist die Durchführung eines kosteneffizienten Monitorings, das verlässliche Aussagen über Teilbereiche der Anbaufläche zulässt. Dieses kann durch die Verwendung von Klebtafeln erreicht werden, sofern Korrelationen mit den Anzahlen der Zielorganismen im Bestand hergestellt werden können und sich auf zukünftige Saisonen übertragen lassen. In dieser Arbeit wird geprüft, ob die genannten Voraussetzungen für ein Monitoring der Gewächshaus Weißen Fliege *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae), sowie ihrer natürlichen Gegenspieler *Encarcia formosa* Gahan (Hymenoptera: Aphelinidae) und *Macrolophus pygmaeus* Rambur (Hemiptera: Miridae) erfüllt sind.

In Kapitel 1 wird gezeigt, dass der Fang einer Gelbtafel Aussagen über die Anzahl von *T. vaporariorum* Nymphen im Bestand auf 170 m² zulässt. Die Aussagekraft der Korrelationen unterschied sich in Bezug auf verschiedene Stadien im Bestand, mit Adulte < Nymphen < Nymphen (eine Woche zuvor). Der Fang von ≥ 6 *E. formosa* / Klebtafel zeigte eine erfolgreiche Schädlingskontrolle an. Da es für die Raubwanze *M. pygmaeus* keine Literaturangaben zur Farbattraktivität gab, wurden in Kapitel 2 die beiden kommerziell meist genutzten Klebtafeln, Gelb- und Blautafeln, im Wahlversuch getestet. Es wurde eine moderate und gleichwertige Anziehungskraft beider Farben festgestellt. Im Gewächshausversuch korrelierten die Fänge beider Tafeltypen mit der Populationsdichte im Bestand, wobei insgesamt mehr Tiere auf blauen Tafeln gefangen wurden. Da sich Gelbtafeln gleichzeitig für ein Monitoring des Schädlings eignen, empfiehlt sich die Verwendung dieses Tafeltyps. Die Validierung dieser Ergebnisse erfolgt in Kapitel 3, wo die ermittelten Korrelationen für die Vorhersage der Populationsdichten im Bestand in einer Folgesaison genutzt werden. Es zeigte sich, dass das

Überschreiten einer zu Testzwecken festgelegte Schadschwelle für *T. vaporariorum* Nymphen richtig vorhergesagt werden konnte. Für Adulte konnte letzteres nicht validiert werden, da die Vorhersage stets unter der Schadschwelle lag. In beiden Fällen wurden die Populationsspitzen stark unterschätzt. Eine erfolgreiche Schädlingskontrolle konnte sowohl für *E. formosa* als auch für *M. pygmaeus* sicher angezeigt werden. Die Genauigkeit der Vorhersage beschränkte sich für *E. formosa* auf hohe Parasitierungsraten, während die Populationsdichte von *M. pygmaeus* durchgehend verfolgt werden konnte. Das Sparpotential eines Monitoring basierten Nützlingseinsatzes konnte gezeigt werden. Auf Basis dieser Ergebnisse wird in Kapitel 4 das Konzept und die Realisierung einer Entscheidungshilfe-Software vorgestellt.

**Stichwörter:** Klebetafel, Monitoring, Entscheidungshilfe,

*Trialeurodes vaporariorum*, *Encarsia formosa*, *Macrolophus pygmaeus*

# General Introduction

Integrated pest management (IPM) has become standard in crop production in Europe, and is of increasing importance worldwide (De Maeyer et al. 2002; van Lenteren 2007). The basic idea of IPM is to rely on naturally occurring, modified or introduced biological control to decrease the equilibrium level of a pest below economic relevant densities. Chemical control is used as necessary and in a manner that is least disruptive to progressive biological control (Stern et al. 1959). Although predatory ants were used in China for biological control already in the year 300 (van Lenteren 2007), an important step to make IPM practicable for growers on a large scale, was the availability of mass-reared beneficials starting in the late 20's. At that time, based on the observation of black whitefly pupae in a tomato greenhouse, Speyer (1927) identified the parasitoid *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae), and within a few years the first mass rearing of the beneficial for commercial use was established. Another cornerstone was the definition of thresholds for pest densities, at which corrective measures have to be taken. The most applied threshold of that kind is the economic injury level (EIL), defined as the pest density at which the expected damage equals the cost of control measures (Stern et al. 1959). This level depends amongst others on the crop, the season and the geographic area of crop production. Because control measures at best should avoid economic damage, Stern et al. (1959) additionally defined the economic threshold (ET) as the pest density at which control measures have to be taken to prevent the pest from reaching the EIL.

Reading about the concept of IPM, one is amazed by the increase of complexity it must have implied to pest management practice of those days; the former use of broad spectrum insecticides in standard intervals shall now be replaced by a concept of self-regulated equilibria of pests and their natural enemies, accepting certain pest densities beneath economically relevant levels. From a grower's perspective, application of this concept translates into increase of workload due to a more detailed monitoring of pests, the extension of monitoring to beneficials, and the need for education about biology of pest and beneficials as well as about selectivity of pesticides. At this point of time the reader most certainly asks oneself: "why should growers adopt this concept?" The main driver was not the belief in self-regulation of pests or to reduce the use of agrochemicals to increase environmental safety. Chemical control measures simply failed at that time, due to increasing resistance of major pests and the upcoming of secondary pests in the absence of natural enemies, both due to the frequent use of broad spectrum insecticides. Two important examples from cotton production are the resistance of the American bollworm *Helicoverpa armigera* and the arising problems with formerly naturally controlled spidermites (*Tetranychus spp.*) (van Lenteren 2007).

Since that time complexity in pest management kept increasing, because more beneficials and also an increasing portfolio of selective chemicals and biologicals became commercially available. Especially in protected crops, were pest management to date often relies mainly on the introduction of beneficials, the use of agrochemicals with minimal side effects on natural enemies became crucial. In principal, with view on the adoption of biological control, we can differentiate between three types of crop. Crops where the presence of natural enemies plays no or minor role for decision making, i.e. pest control depends mainly or entirely on chemical control. Such crops are to date many broad acres, such as rice, corn or rape, but also many ornamentals. Then there are crops were growers are aware of the ecosystem services provided by natural enemies, and try to conserve them in the crop. Prominent examples are grape and many citrus cultures, in which the presence of predatory mites is often monitored and growers use predominantly selective insecticides for pest control. Furthermore there are crops, in which the majority of pests is controlled by the introduction of natural enemies, and were chemical control is only used as a corrective measure if biological control failed. They are typically intense cultivated, high value vegetable crops in protected agriculture.

In order to apply the IPM approach in agriculture, one needs to estimate the current pest pressure to predict the development of pests. However, for an accurate prediction it is not enough to know about the pest but also about its natural enemies (Binns and Nyrop 1992). For instance, the same pest density may never reach economically relevant densities if there are enough natural enemies in the crop but will get out of hand immediately, if natural enemies are absent. To estimate the control status of a pest, i.e. pest and natural enemy densities, a comprehensive monitoring has to be carried out. To develop an efficient monitoring, two main questions should be answered: first, which accuracy is needed for the estimation of the population densities? And second, which workload is acceptable? Clearly, answers on these two questions will differ, when given by a scientist and a grower. Whilst in scientific experiments high workload is acceptable to reach maximal accuracy, for growers the time spent for monitoring has to pay off economically. One result of this discrepancy is that many meaningful monitoring schemes are described in scientific literature, whereas their adoption into commercial growing systems is rather low. The principal gap between science and practice is increasingly recognized by the scientific community and is progressively part of the discussion at international conferences, resulting in a number of recent key notes addressing this topic (Hall 2014; Murphy 2014; Smith 2014). For monitoring schemes it can be stated that, the more time-consuming and costly the proposed scheme, the less likely its adoption in practice. A recent survey with 220 IPM and non-IPM farmers in Thailand revealed that for 80 % of non-IPM farmers, the labor of monitoring and the lack of knowledge about pests and beneficials were main reasons against adoption of IPM practice (Timprasert et al. 2014). A good example for a time-saving monitoring approach is the use of sticky traps in agriculture (Pizzol et al. 2010). These traps are cheap, easy to handle and trapped insects can be detected and counted much faster, as compared to direct ratings on plants. As a consequence, such traps are widely applied for monitoring in crop production (Gillespie and Quiring 1987; Natwick et al. 2007; Pinto-Zevallos and Vänninen 2013), although they are still a hurdle for large farms (Timprasert et al. 2014). Currently, another advantage of these traps in terms of labor emerged: Due to their even surface and the fixed position of the trapped insects, they possess all requirements for automated identification and counting of insects, using image processing software. Automation of insect counts reduces the workload largely, and hence will support the adoption of more comprehensive monitoring schemes into practice in near future. To date the number of devices for such automation available on the market and the number of arthropods recognized by these products is very limited. However, there is a high interest of growers and companies and accordingly much ongoing research towards new products to fill these gaps (Cho et al. 2008; Guarnieri et al. 2012; Qing et al. 2012; Xia 2012).

To increase attraction of target insects to sticky traps, visual or olfactory cues may be used. For many arthropods, visual cues are important for host plant finding, and therefore include colors of host fruits and plants. To date yellow and blue traps are widely applied for monitoring in practice. Yellow traps are considered to be perceived as a light green by most insects (Mellor et al. 1997) and can be assumed to imitate young shoots of host plants, explaining their attractiveness to a wide range of insects. They are attractive to insects from several families, including Diptera, Coleoptera, Homoptera and Hymenoptera (Hoback et al. 1999). For blue traps however, the reason for attraction is unclear, but they are rather selective for thrips, mainly *Frankliniella occidentalis*, and are also attractive to sawflies in general (Hoback et al. 1999; Johansen et al. 2011). Olfactory cues include for instance components of sex pheromones and host fruit volatiles (Reynolds and Prokopy 1997; Guarnieri et al. 2012). Depending on the applied cues and the target insect, attraction distance and selectivity of traps vary largely, both being highest for the use of pheromones. Long distance attraction is clearly an advantage as it decreases the number of traps needed per area, and thereby also monitoring workload. High selectivity of a trap reduces by-catch, which makes counting of the target insect easier and helps preserving natural enemies and pollinators in the crop; on the other hand, if the by-catch includes natural enemies of the target pest, information content of the trap catch regarding pest control status is increased.

In any case is trap catch used for estimation of pest or beneficial population densities on crops.

Although everyone intuitively agrees on this statement, little attention to its implications is spent in practice. Growers are not interested in the numbers of insects they count on a trap, but use it as an indicator for the infestation level on their crop. They intuitively assume that there is a relation between the number of insects trapped and the number that is present on their crop. Also the use of thresholds in IPM relates to the damage a specific pest causes on the crop, not to its numbers on traps. In literature however, there are many examples showing that a trap catch does not necessarily translate into a certain pest or beneficial density on crop, at least not when applied at practice relevant densities (Gillespie and Quiring 1987; Hoffmann et al. 1997; Kim et al. 1999; Hoelmer and Simmons 2008). It can be assumed, that due to the bias against publication of negative results, the real number will be even higher. But the validity of monitoring results is vital for the quality of decision making in crop protection. Therefore, accuracy of monitoring schemes need to be evaluated under practical conditions, for each target arthropod and in each crop. Furthermore, decision rules based on these monitorings need to be validated with independent data sets, generated under practice conditions. However, because work load is a limiting factor for commercial growers, a certain degree of imprecision needs to be accepted. The latter may be compensated by conservative decision rules that limit underestimation of pest pressure and development. Ideally biological control, plant resistance, and cultural practices maintain fluctuating pest populations below economic injury levels (Binns and Nyrop 1992). To assure this, the introduction of natural enemies is often carried out at begin of the growing season, or when the pest is first detected. Once the pest density reaches the economic threshold, introductions of beneficials alone will normally not control the pest effectively, and a selective insecticide has to be applied as a corrective measure.

Once a comprehensive and applicable monitoring is established and combined with appropriate decision rules, the information content provided needs to be processed and presented in an optimal manner. To date many guides for rules of good agronomic practice are given in form of brochures, handouts or online databases. However, the increasing complexity in crop production and the need for time efficiency in the whole production process, sets boundaries to the practicability of these measures. Decision support systems (DSSs) can overcome application hurdles by supplying automatically generated recommendations to growers for all kind of agricultural decisions. In broader content, this idea translates into the so called “precision agriculture” approach that includes decisions on optimal fertilization, water supply, disease control, pest management and even on the optimal crop to grow depending on climate and soil properties (McBratney et al. 2005). For pest management decisions the main parameters influencing the decision are the crop and cultivation type, the crop management, the climate conditions and the actual densities of pests and natural enemies on the crop. In this context, the crop type limits the number of potential pests and also the number of natural enemies that will be effective, as well as the number of chemicals that are registered for use. The climate conditions, together with the actual pest and beneficial densities, form the basis for prediction of the pest and beneficial population growth based on their specific life history parameters, and accordingly the realization of critical pest densities. The growing period limits the number of chemicals, due to applicability at flowering stage and pre-harvest intervals, but also the need for additional beneficial introductions towards the end of the cropping season. DSSs can help to optimize, standardize and accelerate pest management decisions in this complex environment (Knight 1997). To reach acceptance in practice, the underlying decision rules of a software need to be adjustable by the grower. That is especially true for the accepted pest density, because on the one hand there is not a practice relevant economic injury level for every pest available. On the other hand, even if such level exists, the pest density accepted by each grower varies. Therefore, one rule applies to every recommendation in pest control: the last decision is in the responsibility of the grower.

The aim of this work was to develop a comprehensive, low-cost monitoring approach, and to implement it in the concept of a DSS for arthropod pests in protected agriculture, ideally converted into a software tool. Against this background, it was of high importance to select a crop – pest – natural enemy system, which fulfills all requirements for a proof of concept study. A more intense monitoring is more likely to be applied in intense high value crops, such as greenhouse vegetables. In Germany, the production of greenhouse vegetables is still a niche sector. However, 4.45 % of the vegetable harvest was produced in greenhouse production, representing only 1.15 % of the total production area (BMEL 2014), showing the intensity of production. Globally speaking, tomato is the most important greenhouse vegetable, being an intensively produced high value crop with highly specialized production, generating average yields of about 0.5 million kg / ha in The Netherlands and Belgium (FAOSTAT 2015). Because of the regular use of beneficials in this crop, the information on natural enemy establishment is of high importance. If growers invest in the release of natural enemies and rely on their performance in pest control, it can be assumed that they are also willing to invest in tracking biological control efficiency. Therefore and because of the relatively low number of important pests, tomato was selected as a model system for this study. The major pest of this crop, the Greenhouse Whitefly *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae), is commonly controlled by *E. formosa*, *Macrolophus pygmaeus* Rambur (Hemiptera: Miridae), or a combined use of both species. Pest and natural enemies comprise an alate adult stage, making the approach of a sticky trap monitoring promising. In this study, I explored the potential of compiling and processing information on pest occurrence, damaging levels and biological control, with sticky traps as a single monitoring tool.

# Chapter 1

## Yellow traps reloaded: What is the benefit for decision making in practice?[1]

### Abstract

Sticky traps are a standard tool for monitoring alate arthropod pests in greenhouses. However in practice evaluation of traps over the whole growing season is rarely done. For decision making by growers, sticky traps are often only used for detection of pest presence. The reason behind is that although many studies show that pest population densities can be estimated using sticky traps under experimental conditions, validation under growing conditions and monitoring of beneficials are often lacking. In the current study we evaluated whether trap densities recommended for practice are sufficient to estimate pest population densities of *Trialeurodes vaporariorum* (Hemiptera: Aleyrodidae) and its natural enemy *Encarsia formosa* (Hymenoptera: Aphelinidae) in protected tomato cultures throughout the growing season.

Our results show that trap catches provide reliable information about pest densities, in which correlations differed for specific developmental stages, i.e. adults < nymphs < nymphs (previous week). A single yellow sticky trap provided reliable information on nymphal density in the tomato crop on an area of at least 170 m². A rapid increase of parasitoid trap catches indicated high parasitism. In our experiments, a total trap catch of ≥6 parasitoids / trap was a

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[1] E. Böckmann, M. Hommes and Meyhöfer, R. (2015) Yellow traps reloaded: What is the benefit for decision making in practice? Journal of Pest Science **88** (2) 439-449

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suitable threshold for sufficient natural enemy activity in the tomato crop. The implementation of these results in practice and the transferability to other cropping systems are discussed.

**Key words:** Sticky trap, introduction regime, trap density, parasitoid, *Trialeurodes vaporariorum*, *Encarsia formosa*

# Introduction

Monitoring is an essential part of integrated pest management (IPM) with the aim to assure that pest populations are below the economic injury level (EIL). At EIL the costs to control a pest equals the amount of economic damage it inflicts, while below the EIL it is not cost-efficient to control the pest species (Meyer 2003). Monitoring tools and schemes to determine whether the pest population reaches the EIL are therefore of primary importance for plant protection. Their reliability depends on the correlation of monitoring results with actual pest population densities in the crop (Gillespie and Quiring, 1987; Pinto-Zevallos and Vänninen, 2013). For most insects the precision of monitoring increases with higher monitoring efforts (i.e. number of plants inspected, number of yellow traps, etc.). Therefore, the optimal trap density for monitoring has to be determined for each pest species and crop separately. For commercial growers, the monitoring intensity is not only a matter of precision but also of cost and benefit. Thus, growers rarely apply monitoring in its full complexity (Steiner et al. 1999) and often focus on the detection of the first pest occurrence. In practice monitoring is frequently done with a lower trap number and/or larger sample intervals than recommended for best reliability (Cullen et al. 2000). Consequently, estimates of pest densities are often not evaluated as the best source for decision making in IPM (Duffield and Jordan 2000; Hamilton et al. 2006).

Pest and natural enemy monitoring schemes are species specific and are based on direct or indirect observations. Apart from direct counting on the plant, there are several trapping systems available on the market, such as pheromone traps, suction traps and coloured sticky traps. The use of sticky traps is the most common technique to monitor alate pest species, i.e. thrips, white flies, and aphids in greenhouse vegetables and ornamentals (Ohnesorge and Rapp 1986; Gillespie and Quiring 1987; Cloyd 2009). Furthermore, several beneficials are attracted to sticky traps and can be monitored (Parrella et al. 1991; Beers 2012). The attractiveness of sticky traps depends on shape, colour and position (i.e. height) in the crop (Ohnesorge and Rapp 1986; Vernon and Gillespie 1995; Kim and Lim 2011).

But even if monitoring tools are established the estimation of pest population densities in the crop might be unclear. For example, two studies which investigated the use of yellow sticky trap catches for estimation of population densities in *Trialeurodes vaporariorum* (Hemiptera: Aleyrodidae) came to conflicting results. Gillespie and Quiring (1987) found that yellow trap catches correlate with adult numbers on plants only up to 1 trap per 7m² while Kim et al. (1999) found correlations up to 1 trap per 50m$^2$. In contrast, for monitoring carried out by commercial growers a density of 1 yellow sticky trap per 100-250m² is advised in Germany (survey of 13 plant protection advisors and beneficial producers, unpublished data) while 1 yellow sticky trap per 500-700 m² is preferred in The Netherlands (Joke de Jong, personal communication). Koppert B.V. as an internationally operating company advices the use of 1 trap per 200m² (Koppert 2013). Basically the examples underline the need for reliable trap density and robust correlations between trap catches and pest population in the crop to optimise decision making.

In IPM the use of beneficials is the first choice when a pest species is detected. The whitefly *T. vaporariorum* is one of the major pests in protected tomato cultivation causing direct damage by sucking plant sap, but more importantly indirect damage by production of honeydew (facilitating sooty mould growth) and virus transmission (De Vis and van Lenteren 2008; Jelinek 2010). Reduced susceptibility and resistance to common insecticides makes chemical control difficult (Karatolos et al. 2010). Therefore, repeated introductions of *Encarsia formosa* (Hymenoptera: Aphelinidae) are standard in IPM of *T. vaporariorum* in tomato crop. Depending on the monitoring effort, introductions are carried out preventively, i.e. starting with fixed timing shortly after planting, or on demand (when first *T. vaporariorum* is detected). In year-round-cultures *E. formosa* is commonly used in combination with the predatory bug *Macrolophus caliginosus* (Hemiptera: Miridae). In that case, introduction of *E. formosa* ends with establishment of *M. caliginosus* in the crop. In tomato summer cultures where only *E. formosa* is released, introduction most often starts with first detection of the pest and is continued until the end of the growing season, or until a fixed number of introductions is realized. However, the official recommendation for growers in North Rhine-Westphalia (Germany) is to stop introduction of *E. formosa* if 80 % of whitefly nymphs are parasitized (Scholz-Döblin 2013). In practice this threshold is rarely used due to the workload for assessment of parasitism rates on plants, although it would save for each release of *E. formosa*, i.e. 30.000 parasitoids, 180-270 € per hectare (calculation based on Scholz-Döblin (2013)). An efficient alternative strategy to monitor parasitism rates might be yellow traps, since *E. formosa* can be frequently observed on these traps (Parrella et al. 1991). So far two studies indicate that parasitoid numbers on yellow sticky traps in tomato greenhouses increase with increasing parasitism rates (Webb and Smith 1980; Van de Veire and Vacante 1984), but without specific consideration in decision support systems. Additionally, the use of yellow traps to estimate pest densities and to decide on established control becomes more feasible with the ongoing development of (semi-) automatic devices for trap assessment (Cho et al. 2008; Guarnieri et al. 2012; Xia 2012). A first example for such a device is the Scoutbox® (BLGG, Netherlands) which can markedly reduce workload of continuous monitoring on behalf of trap catches. It is therefore of major interest to define the relationship between pest densities – trap catches – trap densities and the benefit of intensive monitoring programmes for growers to increase the acceptance of real IPM in practice. Knowledge of the actual population densities is also of special interest for integration of dynamic modelling into decision making. Forecasting population development may enable the estimation of critical pest densities weeks before the respective economic injury level is reached and provides freedom of action. Furthermore, adequate automated monitoring may enable growers of large greenhouses to decide on pest management separately for parts of their greenhouse with the benefit of reduced applications of insecticides and accordingly introductions of beneficials.

With these innovative developments in mind we designed greenhouse experiments to evaluate the reliability of sticky traps for estimation of *T. vaporariorum* and *E. formosa* densities in tomato crops. Furthermore, we evaluate which monitoring density is needed and if introduction regimes of *E. formosa* can be modified based on trap catches of the parasitoid.

# Methods

## Experimental setup

Experiments were carried out at the Julius Kühn-Institute in Braunschweig (Germany) in a 170 m$^2$ greenhouse and two neighbouring greenhouse chambers, each 40 m$^2$. Tomatoes (cultivar: Campari; Enza Zaden Deutschland GmbH & Co. KG) were planted end of April 2012 at calendar week 16 / 17 with 1.25 m distance between rows, resulting in 6 rows each with 36 plants in the large and 4 rows each with 12 plants in the small greenhouses. Plants were allowed to grow up to 2.5 m. Thereafter they were turned over and forced to grow downwards. In the large greenhouse 10 yellow sticky traps (i.e. 1 trap / 17 m$^2$) (dry-glue yellow sticky plates, Horticoop b.v., The Netherlands) and in the smaller chambers 2 yellow sticky traps (i.e. 1 trap / 20 m$^2$) were hung up on top plant level between plants within rows (Figure 1). Position was adjusted until maximum plant height was reached. Trap size was 24.5 cm long by 10 cm wide. As initial population 96 adult *T. vaporariorum* of each sex were released in the large greenhouse (4 release points with 48 adults each) and 24 in the greenhouse chambers (1 release point with 48 adults each) at May 16th. All individuals originated from a permanent rearing on tobacco (Leibniz Universität Hannover, Institute of Horticultural Productionsystems, Germany) and were reared for at least two generations on tomato under greenhouse conditions (22.5 ± 5.5 °C [mean ± SD], 44-80 % RH).

*E. formosa* were purchased from Katz Biotech AG (Baruth, Germany). The parasitoids were supplied as black (i.e. parasitized) nymphs on paper cards, each with approx. 50 individuals. Quality was confirmed by computing percentage of empty black nymphs on 4 cards in the standard- and 10 cards in the experimental treatment two weeks after introduction. Eclosion at any time was 93 ± 0.05 % in the standard and 90 ± 0.11 % in the adapted treatment (means ± SD).

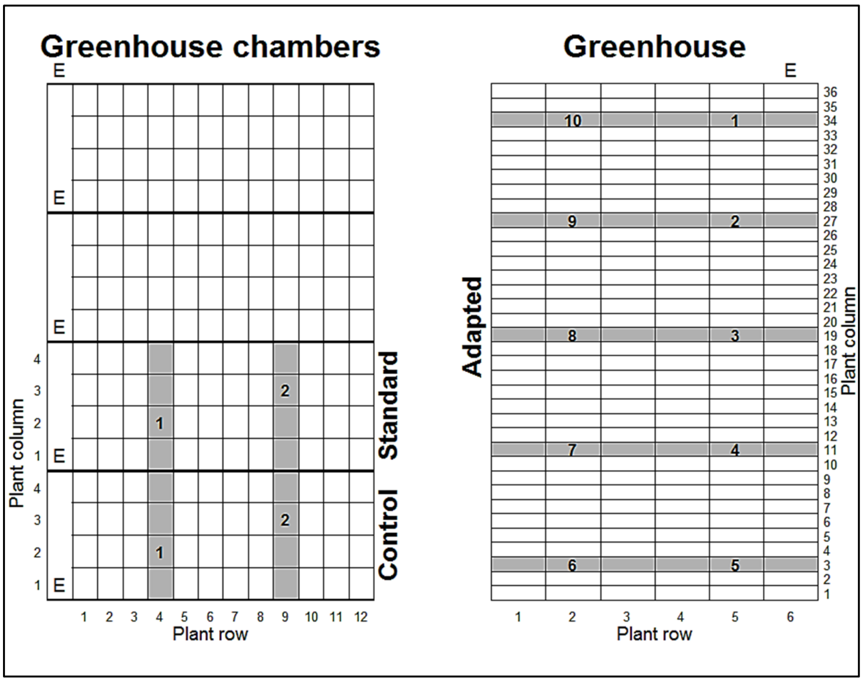

**Figure 1** Position and numbering of yellow sticky traps (bold numbers), sample plants (grey boxes) and Entrance (E) in the control, standard and adapted treatment. The growing area was 40 m$^2$ for each greenhouse chamber (standard and control treatment) and 170 m$^2$ for the large greenhouse (adapted treatment). Note that different size of cells does not indicate different distance between rows or plants.

Three different treatments, a control, an adapted and a standard treatment, differing in the *E. formosa* release frequency, were realised. In the large greenhouse (**adapted treatment**) and one of the greenhouse chambers (**standard treatment**), 5 *E. formosa* per $m^2$ were released on demand every 2nd week, i.e. when the first whitefly was monitored on a yellow sticky trap (May 23rd in both treatments). While release of *E. formosa* was terminated in the adapted treatment as soon as average trap catch of parasitoids increased 3-fold (last introduction at July 27th), introductions in the standard treatment were continued until the end of the experiment (last introduction at September 5th). The second small greenhouse chamber served as **control treatment** without release of *E. formosa*. However due to exponential population growth of whitefly population, the control was terminated at August 1st. In all greenhouses fungicides were used to control powdery mildew (July 3: Topas®, Syngenta; July 13: Collis®, BASF; August 3: Ortiva®, Syngenta).

Adult *T. vaporariorum* and *E. formosa* were counted weekly on yellow sticky traps in all treatments. Additionally, whiteflies (adults, 3rd and 4th instar nymphs) and parasitoids (adults, black nymphs) were counted directly on tomato leaves. Counts were taken on 30 plants in the large greenhouse and on 8 plants in each small chamber (Figure 1) on the lower surface of 3 tomato leaves at lower, intermediate and upper plant level, i.e. 9 leaves per plant in total. All counts were taken at weekly intervals from May 23rd till September 12th 2012. Since it was observed that the parasitoid *E. formosa* was able to disengage itself from the commercial yellow sticky traps, additional coating with insect glue (Temmen Insekten-Leim, Temmen GmbH) was necessary. Therefore reliable data on *E. formosa* trap catches are available only from July 4th onwards.

Temperature was rather constant throughout the experimental time in all greenhouses, with 21.24 ± 3.84°C in the adapted-, 21.03 ± 3.54°C in the standard- and 21.83 ± 4.16°C in the control treatment (mean ± SD).

## Statistical analysis

Averages of insects counted per plant as well as of insects caught on several sticky traps were calculated per week. Data were $\ln(x + 0.01)$ transformed prior to analysis. The data point for whitefly nymphs collected on June 20th in the standard treatment was excluded from the analysis because the extremely low value was most likely caused by a sampling error.

Linear models were fitted for number of adults and nymphs on plants as explanatory variable, respectively, and with adult trap catches as dependent variable. Additionally models with whitefly nymphs on plants of the previous week as explanatory variable were calculated. ANOVA was used to test whether fitted linear models for whitefly differed between treatments. Trapped adult parasitoids were analysed in a similar way with parasitism rate as explanatory variable.

Data collected in the large greenhouse (adapted treatment) were also used to test whether all single traps provide useful estimates of population densities on plants for the whole greenhouse (170 m²), again by fitting linear models. These calculations were done only with *T. vaporariorum* nymphal counts and *E. formosa* parasitism rates of the previous week because of highest $R^2$ values in the former analysis.

Two approaches were used to estimate how many parasitoids need to be trapped to indicate that pest control is established and natural enemy introductions can be discontinued. First, the model fitted for the adapted treatment was used to calculate the threshold number of parasitoids on a sticky card needed for indication of an 80 % parasitism rate. Second, progression of parasitoid numbers on single sticky traps were analysed graphically to define a range of parasitoid thresholds indicating an 80 % parasitism rate.

The prediction accuracy of the different thresholds was determined with all single trap data for parasitoid counts between July 4th and August 15th (N = 70). Later dates were excluded because they are not of interest for indication. Results were rated as true when counts were below the threshold and parasitism rate below 80 %, or counts were above the threshold and parasitism above 80 %. They were rated as false when counts were below the threshold and parasitism above 80 %, or counts were above the threshold and parasitism rate below 80 %. To identify the threshold with the highest reliability true-false ratios were analysed by chi-square tests (likelihood ratio), allowing an error rate of 0 % for false negative indications and 10 % for false positive indications. All statistical analyses were carried out in R (version 2.15.1).

# Results

## Whitefly monitoring with yellow sticky traps

*Trialeurodes vaporariorum* adults were trapped already one week after release on 50 % of traps in the standard treatment, and 80 % of traps in the adapted treatment. By the second week *T. vaporariorum* was present on all traps. Numbers of adult *T. vaporariorum* caught on traps followed nymphal and adult counts on the crop in all treatments (Figure 2). Maxima of trap catches and adult counts on plants were recorded in August in the standard- and the adapted treatment. In the control treatment both measures still increased until end of the experiment at August 1st.

**Table 1** Linear regression models to examine correlation between yellow sticky trap catches and *T. vaporariorum* density on the crop. Three different explanatory factors, i.e. adults, nymphs and nymphs counted in the previous week, were considered in each treatment (adapted, standard, control) to estimate adult trap catches. Models were fitted based on weekly mean values (all sample plants, all traps). Estimates are based on logarithmized values.

| **Treatment** | **Factor** | **Estimate ± SE** | **p** | $df_{num}$<br>$df_{den}$ | **F** | $R^2$ |
|---|---|---|---|---|---|---|
| Adapted | Intercept | 3.974 ± 0.287 | **<0.0001** | 1 | 13.8 | 0.48 |
| | Adults | 1.276 ± 0.343 | **0.0021** | 15 | | |
| Standard | Intercept | 2.936 ± 0.406 | **<0.0001** | 1 | 13.9 | 0.48 |
| | Adults | 1.381 ± 0.370 | **0.002** | 15 | | |
| Control | Intercept | 1.718 ± 0.364 | **0.0011** | 1 | 116.6 | 0.92 |
| | Adults | 2.435 ± 0.226 | **<0.0001** | 9 | | |
| Adapted | Intercept | 3.151 ± 0.185 | **<0.0001** | 1 | 23.2 | 0.61 |
| | Nymphs | 0.384 ± 0.082 | **0.0002** | 15 | | |
| Standard | Intercept | 3.107 ± 0.434 | **<0.0001** | 1 | 9.5 | 0.39 |
| | Nymphs | 0.600 ± 0.194 | **0.0075** | 15 | | |
| Control | Intercept | 2.433 ± 0.620 | **0.0035** | 1 | 28.8 | 0.76 |
| | Nymphs | 1.035 ± 0.193 | **0.0005** | 9 | | |
| Adapted | Intercept | 3.233 ± 0.122 | **<0.0001** | 1 | 55.91 | 0.80 |
| | Nymphs (prev. wk.) | 0.400 ± 0.054 | **<0.0001** | 14 | | |
| Standard | Intercept | 3.355 ± 0.327 | **<0.0001** | 1 | 22.3 | 0.61 |
| | Nymphs (prev. wk.) | 0.673 ± 0.142 | **0.0003** | 14 | | |
| Control | Intercept | 3.752 ± 0.382 | **<0.0001** | 1 | 39.2 | 0.83 |
| | Nymphs (prev. wk.) | 0.742 ± 0.119 | **0.0002** | 8 | | |

Maxima of nymphal counts on plants were earlier in all treatments, i.e. mid of July. Linear regression models of *T. vaporariorum* counts on traps as a function of nymphal and adult counts on the crop for all treatments are shown in Table 1. Considering the average value of whiteflies from 10 traps, all linear models were highly significant with $r^2 \geq 0.39$. Nymphal counts on the crop of the previous week show markedly higher correlation than nymphal counts of the same week in all treatments. Nevertheless, highest correlation in all regression models was always found in the control treatment, i.e. without natural enemy release (Table 1).For nymphs of the current or previous week, the treatment (i.e. release of natural enemies and greenhouse size) did not influence the result of the linear regression models significantly (ANOVA; $F = 0.1$; df = 2, 41; $p = 0.9$ and $F = 1.5$; df = 2, 38; $p = 0.24$). In contrast there was a significant treatment influence when models were based on adult counts on the crop (ANOVA, $F = 7.2$; df = 2, 41; $p = 0.0021$).

### *Whitefly density: Information content of single traps on 170m²*

Results so far were based on average numbers of whiteflies on 10 yellow sticky traps. Since growers use 1-2 traps on 100-250 m² we analysed if single traps were representative for 170 m², i.e. the whole large greenhouse. Because of the superior performance in the previous analysis, we only calculated regression models based on nymphal data on the crop of the previous week. Linear models were significant ($p < 0.01$) for all traps ($N = 10$). Results indicate that the explanatory power of these models was reasonable with $r^2$ ranging from 0.50 to 0.71.

## Parasitoid monitoring with yellow sticky traps

Parasitoids were detected on traps only when coated with additional glue. At July 4th parasitoids were caught on 50 % of traps in the adapted treatment. First record in the standard treatment was at August 1st on 50 % of traps. In the following weeks parasitoids were continuously recorded on traps in both treatments. Trends in trap catches followed parasitism rate on the crop in both treatments (Figure 3). A rapid increase in parasitoid trap catches was observed in both treatments between July 25th and Aug 8th. Whilst trap catches in the adapted treatment decreased thereafter in coincidence with discontinued parasitoid introductions, they still increased in the standard treatment

(Figure 3). Adult counts of *E. formosa* on plants were inconsistent and low throughout experiments.

Linear regression models of *E. formosa* counts on traps as a function of black nymphs and adult counts, as well as for parasitism rates are shown in Table 2. For trap catches as a function of adult numbers on plants, none of the fitted linear models was significant (Table 2). In contrast significant linear models with $R^2$ ranging from 0.50 to 0.78 could be fitted for adult trap catches as a function of black nymphs in the crop and correlation increased for linear models considering black nymphs of the previous week (Table 2). Also for trap catches as a function of parasitism rate, significant linear models could be fitted for both treatments with $R^2$ of 0.56 in the adapted and 0.85 in the standard treatment (Table 2). Parasitism rates and black nymphs in the standard treatment explained parasitoid trap catches to larger extent than in the adapted treatment.

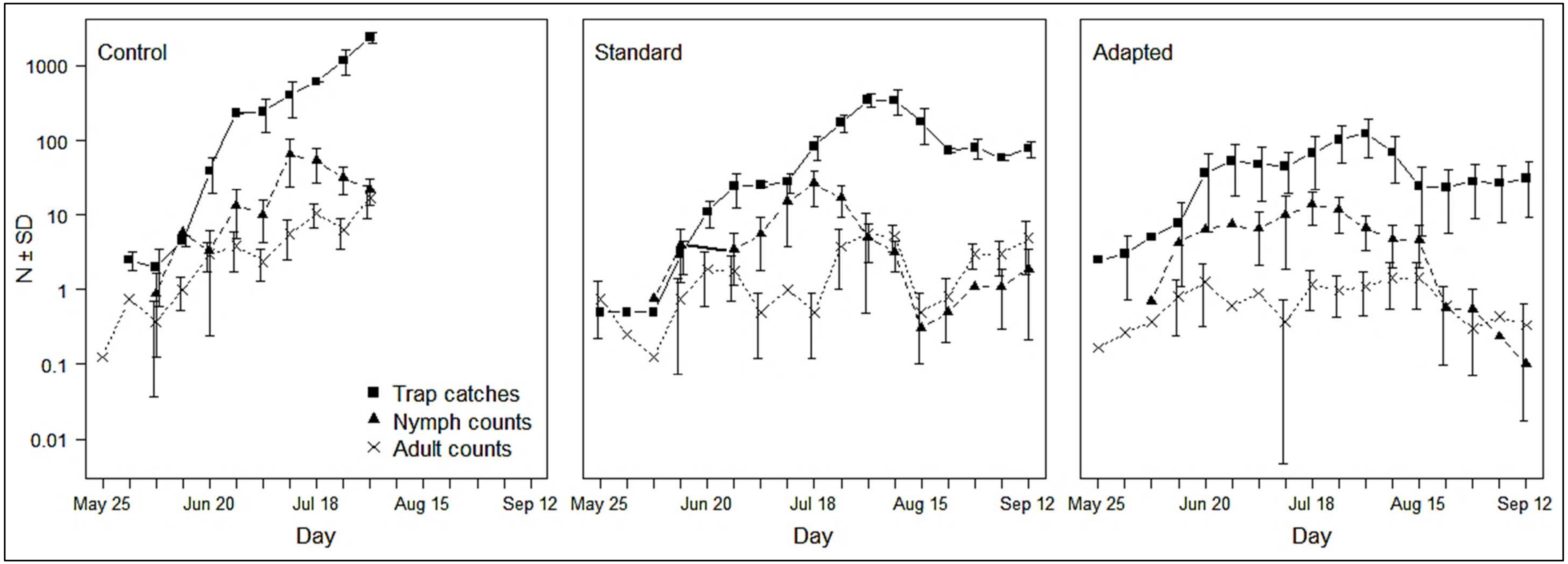

**Figure 2** Development of average nymph and adult counts (± SD) per plant and week (adapted treatment N = 30; control and standard treatment N = 8) and adult trap catches (adapted treatment N = 10; control and standard treatment N = 2) in the adapted-, standard- and control treatment. Data is plotted on logarithmic scale and zero values were excluded from all graphs. The control treatment was terminated Aug 1st due exponential growth of white flies and immigration of *E. formosa* starting at Jul 25th. Larval data of June 20th was excluded for the standard treatment, because low counts indicated sampling error.

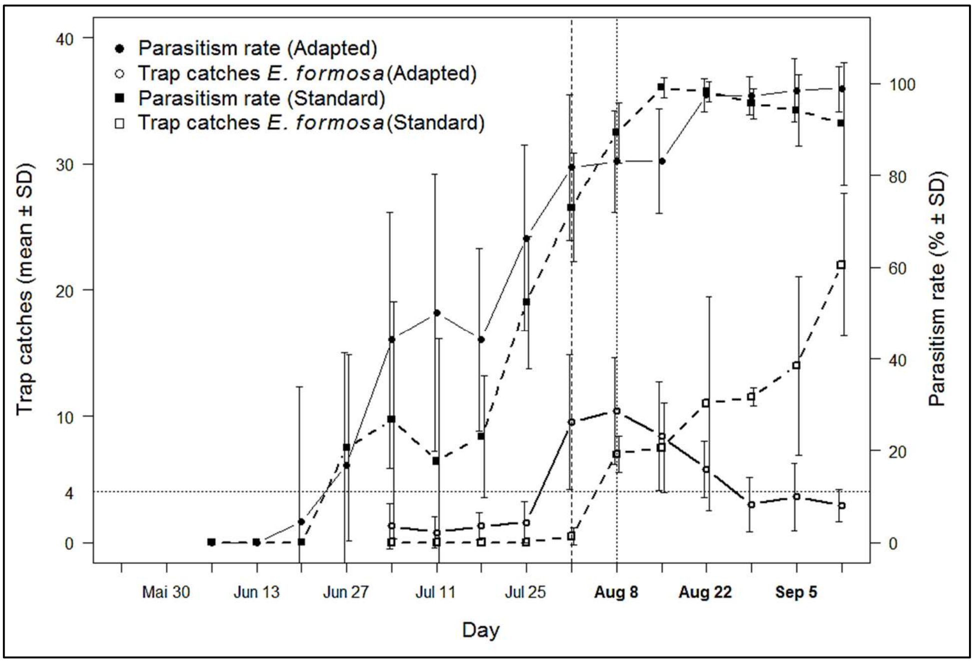

**Figure 3** Development of average parasitism rate (adapted treatment N = 30 plants, standard treatment N = 2 plants) and average number of *E. formosa* trapped on yellow sticky traps (adapted treatment N = 10 YT; standard treatment N = 2 YT) (± SD). The vertical lines indicate the time at which 80 % parasitism was reached (black dashed = adapted treatment, black dotted = standard treatment). In the adapted treatment weekly release of *E. formosa* was stopped at August 1st, while it was continued to the end in the standard treatment (bold written dates). The horizontal dotted line indicates the threshold of 4 *E. formosa* / trap, which was assessed as indicator for established control.

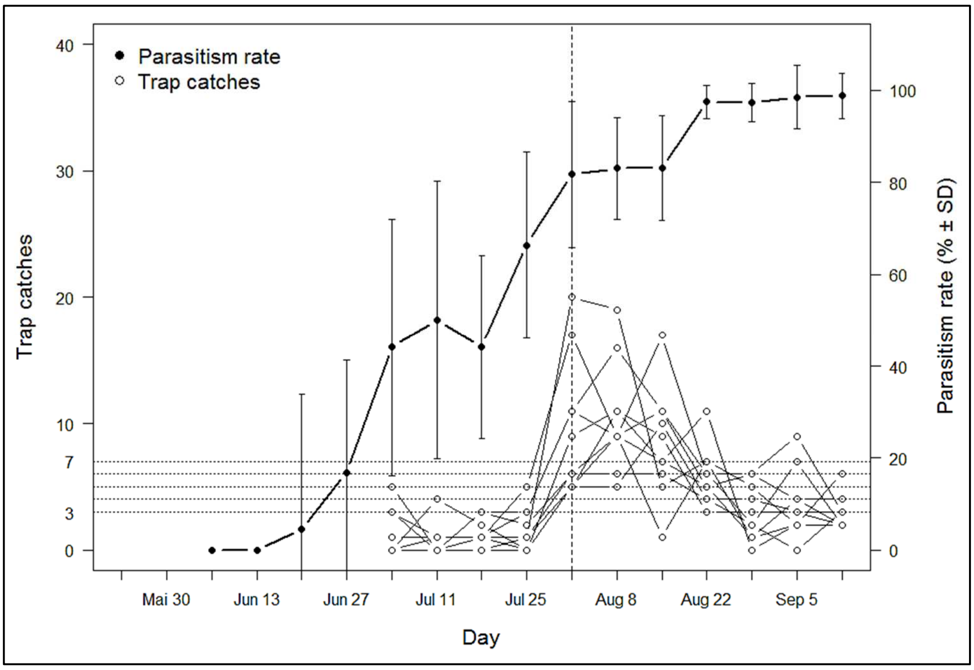

**Figure 4** Development of average parasitism rate (N = 30 plants) and number of *E. formosa* trapped on single yellow sticky traps in the adapted treatment. The vertical dashed line indicates the date when 80 % parasitism rate was reached. The horizontal dotted lines indicate threshold levels assessed as indicators for established control, ranging from 3 to 7 *E. formosa* / trap.

### *Parasitism: Information content of single traps on 170m²*

Since growers use 1-2 traps on 100-250 m² we analysed if single traps were representative for 170 m², i.e. the whole large greenhouse. For *E. formosa* we focused on trap catches as a function of parasitism rate, but significant linear models could only be established for 6 of the 10 traps ($p < 0.05$), with $R^2$ ranging from 0.37-0.88. However, rapid increase in the number of adult parasitoids caught on yellow traps to total numbers reaching from 5 to more than 15 (Figure 4) might serve as indicator for established biological control. Using the linear regression model ≥ 4 parasitoids have to be caught on a yellow trap to indicate a parasitism rate ≥ 80 % (calculated by the parasitism rate model; Table 2).

**Table 2** Linear regression models to examine correlation between yellow sticky trap catches and *E. formosa* density on the crop. Four different explanatory factors, i.e. adults, black nymphs and black nymphs counted in the previous week, as well as parasitism rate were considered in each treatment (adapted, standard, control) to estimate adult trap catches. Models were fitted based on weekly mean values (all sample plants; all traps). Estimates refer to logarithmized values.

| Treatment | Factor | Estimate ± SE | p | $df_{num}$ $df_{den}$ | F | $R^2$ |
|---|---|---|---|---|---|---|
| Adapted | Intercept | 1.052 ± 0.518 | 0.0726 | 1 | 0.1 | 0.01 |
| | Adults | -0.059 ± 0.243 | 0.8122 | 9 | | |
| Standard | Intercept | -0.068 ± 2.072 | 0.9740 | 1 | 0 | 0 |
| | Adults | 0.198 ± 1.008 | 0.8480 | 9 | | |
| Adapted | Intercept | -2.040 ± 1.094 | 0.0952 | 1 | 8.8 | 0.50 |
| | Black nymphs | 1.172 ± 0.394 | **0.0156** | 9 | | |
| Standard | Intercept | -8.094 ± 2.172 | **0.0047** | 1 | 13.9 | 0.61 |
| | Black nymphs | 2.954 ± 0.793 | **0.0047** | 9 | | |
| Adapted | Intercept | -0.850 ± 0.583 | 0.1786 | 1 | 13.1 | 0.55 |
| | Black nymphs (prev. wk.) | 0.782 ± 0.216 | **0.0056** | 9 | | |
| Standard | Intercept | -6.255 ± 1.142 | **0.0004** | 1 | 32.7 | 0.78 |
| | Black nymphs (prev. wk.) | 2.449 ± 0.428 | **0.0003** | 9 | | |
| Adapted | Intercept | -6.746 ± 2.354 | **0.0186** | 1 | 11.35 | 0.56 |
| | Parasitism rate (%) | 1.846 ± 0.548 | **0.0080** | 9 | | |
| Standard | Intercept | -20.905 ± 2.852 | **<0.0001** | 1 | 52.8 | 0.85 |
| | Parasitism rate (%) | 5.019 ± 0.691 | **<0.0001** | 9 | | |

Additionally a range of suitable threshold values, i.e. 3-7 parasitoids per trap, were identified graphically (Figure 4). The accuracy of all threshold values as indicator for parasitism rates of ≥ 80 % was evaluated for each of the 10 single traps in the adapted treatment and rated as true or false. Results indicate that at the calculated threshold of 4 parasitoids / trap the error rate was 6 %, with 3 false positive indications, i.e. trap catch indicates that parasitism rate of 80 % is reached while in fact it was below that level. At a threshold of 6 parasitoids / trap no false positive indication could be detected, but 9 % showed false negative indications (Table 3).

In practice it is also of high importance that established control is not indicated too early (risk of biological control failure) and not too late (unnecessary introductions). Therefore each of the 10 traps was analysed according to the threshold reached before (early indication), at the same time (in-time indication) or after the parasitism rate reached 80 % (late indication). Results indicate that early indications decreased from 6, 2, 1, to 0 at thresholds of 3, 4, 5, or 6 parasitoids / trap, respectively, while late indications increased from 0, 0, 0, to 3.

**Table 3** Accurateness of several threshold values for number of parasitoids caught on yellow sticky traps, as indicator for parasitism rate above or below 80 %. All weekly counts of parasitoids on yellow sticky traps (n = 70) were rated either as true or false. Results were tested by chi-square test (likelihood ratio) assuming a data distribution of 40:0:27:3, i.e. counts above threshold (TH) and parasitism rate (PR) below 80 % should never occur (grey box), while for counts below threshold and parasitism rate already above 80 % an error rate of 10 % is acceptable (for further explanation see results and discussion)

| Threshold (*E. formosa* / trap) | True (<TH & PR <80 %) | False (≥TH & PR <80 %) | True (≥TH & PR ≥80 %) | False (<TH & PR ≥80 % ) | df | $\chi^2$ | p |
|---|---|---|---|---|---|---|---|
| 3 | 32 | 8 | 29 | 1 | 3 | 13.099 | 0.004 |
| 4 | 37 | 3 | 29 | 1 | 3 | 5.394 | 0.145 |
| 5 | 38 | 2 | 29 | 1 | 3 | 3.942 | 0.268 |
| 6 | 40 | 0 | 24 | 6 | 3 | 1.196 | 0.550 |
| 7 | 40 | 0 | 20 | 10 | 3 | 5.023 | 0.081 |

# Discussion

## Whitefly monitoring with yellow sticky traps

Our study gives first answers on two key questions recently raised in the review by Pinto-Zevallos and Vänninen (2013) on the use of yellow sticky traps in whitefly management. They stressed that the main focus of future investigations should be on the correlation of sessile whitefly nymphs and adult yellow trap catches and on the question whether yellow trap densities used in practice reveal estimates suitable for decision making. Our results show that the actual density of whitefly nymphs and adults on the crop can be accurately described using trap catches (Figure 2). In all experiments correlations were significant and positive (Table 1), and independent of greenhouse size and beneficial regime as long as whitefly nymphs were considered. Correlations of the linear regression models were even higher if the nymphal density of the previous instead of the current week was used, which is in line with results obtained by Kim et al. (1999).

Since adults hatch at the end of the nymphal development in a greenhouse tomato crop within 1-2 weeks (van Roermund 1995) it is reasonable that the correlation with adult whiteflies on traps was best when nymphs on the crop of the previous week were considered. Even a shift of two instead of one week gave good results, but with the view on practical use a more recent estimation is preferred. Little is known about frequency and distance of whitefly migration (Byrne and Bellows 1991), but the highly aggregated distribution of whiteflies (Noldus et al. 1986) indicates a low dispersal rate of adults once a suitable crop is located. Furthermore, short range movements mainly occur near ground level (Gerling and Horowitz 1984; Byrne et al. 1986). However, young whitefly adults move to top plant level after emergence (Martin and Dale 1989) and therefore it is likely that a large proportion of trap catches were recently emerged adults. Therefore, dispersal behaviour of adult whiteflies underline the significant correlation of adult trap catches with nymphal developmental stages of the previous week.

In practice and literature, yellow trap catches are often used to estimate adult population densities (Hall 2009; Pizzol et al. 2010). In our study this correlation was less reliable as compared to the correlation with nymphal counts of the previous week. Three different factors may contribute to this reduced reliability: (1) counting adults on plants is difficult, leading to underestimation of adult population in the crop (2) hatching of adults during the sampling period is not evenly distributed, leading to wrong estimates and (3) simultaneous counts on traps and plants do not take into account that adult trapping on sticky traps is cumulative while adult mortality within the sampling interval cannot be assessed on plants. Nevertheless, Kim et al. (1999) found that estimation of adult densities of *T. vaporariorum* on tomato plants was more accurate as compared to nymphs on the crop. To explain these contradicting results, methodological details have to be compared, which was impossible because the original article is published in the Korean language and only partly in English.

In order to transfer results to practice it is of high interest to optimize the number of yellow sticky traps in the greenhouse to keep workload and costs at reasonable levels. From a survey we concluded that ~1 trap / 100-250m$^2$ is a density acceptable for growers at least in Germany (unpublished data). Our results show that each of the ten yellow sticky traps used in a greenhouse of 170m$^2$ described pest densities with high accuracy. This indicates no need for higher trap densities, but whether even larger areas can be adequately monitored using a single trap remains to be investigated. Nevertheless optimal monitoring areas should be also closely linked to site-specific pest management strategies.

Correlation of adult trap catches with whitefly nymph population density on the crop is mainly limited by the decrease of larval numbers in the end of the season, when adult counts on traps remain at constant levels (Figure 2). Fortunately that part of the season is not very critical in terms of plant protection decisions and hence some overestimation might be acceptable. In the worst case it could lead to needless plant protection measures but critical pest densities will never be missed.

## Parasitoid monitoring with yellow sticky traps

In the present study the number of trapped parasitoids correlated well with the one of parasitized nymphs in both treatments. The better model fit with nymphs of the previous week as explanatory variable is in line with the results presented for *T. vaporariorum*. Nymphs parasitized by *E. formosa* turn black after pupation of the parasitoid. After pupation they develop within 1-2 weeks (van Roermund 1995). In the present study only black nymphs were counted as parasitized. Therefore it is not surprising that the correlation of adult parasitoids on traps with black nymphs on the crop was best when black nymphs of the previous week were considered. As long as yellow traps are sticky enough to trap parasitoids the relationship between trapped parasitoids and parasitism rate can be used to monitor biological control success in tomato. However, the correlation could be approved only for 60 % of the single traps used on 170 m$^2$, indicating the need for doubling the trap densities to monitor parasitism accurately.

Hoelmer and Simmons (2008) did not find correlations between trap catches of the released parasitoid *Eretmocerus emiratus* and parasitized nymphs of *Bemisia tabaci* on Cantaloupe and Watermelon. However, in contrast to our study traps were placed horizontally and in the open field. Furthermore the authors did not consider correlations of trap catches with parasitism rate. Karut and Kazak (2007) were able to correlate trap catches of *Bemisia tabaci* with trapped *Eretmocerus lutea*, but also did not evaluate correlation between parasitoid density or parasitism rate in the crop and trap catches of the parasitoid. Our experimental results show a marked increase of *E. formosa* trap catches which remained on a high level in the subsequent weeks. At the same time parasitism rates of approximately 80 % were reached. A similar increase is described in a study by van de Veire and Vacante (1984) which correlated well with a parasitism rate of approx. 70 %. A first empirical estimate for successful establishment of biological control by *E. formosa* is proposed by Scholz-Döblin (2013) with 80 % parasitized whitefly nymphs (i.e. black nymphs). Hence the present study shows that quantification of natural enemies on yellow sticky traps could be an easy method to monitor natural enemy efficiency. The advantage of the method is two-fold, at first it is a fast and easy method to estimate parasitoid population density compared to visual plant inspections and second natural enemy activity can be monitored in parallel with whiteflies on the same yellow sticky trap.

In our experiments, termination of *E. formosa* introductions at a time when trap catches still increase did not lower parasitoid efficacy as compared to continuing *E. formosa* introductions (Figure 3). Without explicit use of parasitoid trap catches as an indicator also van de Veire and Vacante (1984) stopped *E. formosa* introduction in their experiments, and similar to our study control of *T. vaporariorum* remained stable. The rapid increase of *E. formosa* trap catches can be explained by a behavioural shift of adult parasitoids. At high parasitism rates and hence low densities of suitable hosts, the motivation for patch leaving and searching for a more profitable habitats should increase (Jervis 2005; Wajnberg et al. 2007). For *E. formosa* encountering of black nymphs on a leaflet reduced residence time by 50 % compared to unparasitized hosts (van Roermund and van Lenteren 1995). In consequence trapping of *E. formosa* on yellow sticky traps is more likely at high parasitism rates and a function of increased flight activity. At high parasitism rates, additional introductions of *E. formosa* will therefore not result in improved whitefly control but in higher dispersal activity of the beneficial. The latter is also supported by the increasing numbers of trapped parasitoids towards the end of the season in the standard treatment, as compared to the adapted treatment without further introductions (Figure 3). Although the continued introductions in the standard treatment did not improve whitefly control, the resulting increase in trap catch towards end of the season increased explanatory power of fitted models (Table 2).

Based on our results there are two possible approaches to assess a threshold level for established biological control. On the one hand the linear correlation model can be used to calculate a parasitoid threshold of ≥ 4 *E. formosa* / trap as indicator of 80 % parasitism rate with an error rate of 4.3 %. But in order to achieve acceptance of this new monitoring method in practice it is most important that no failure in biological control is caused by too early indications. Therefore we propose a reliable and robust threshold to guarantee detection of parasitism rates of ≥ 80 %, i.e. successful biological control of *T. vaporariorum*, at 6 or more adult *E. formosa* caught on a single sticky trap within one week. Using that threshold, too early indications could be omitted with the disadvantage of 30 % delayed indications. Combining the results of van de Veire and Vacante (1984), Scholz-Döblin (2013) and our own results, *E. formosa* trap catches should be used to optimize the introduction regime in tomato summer cultures. The proposed threshold was conclusive at practice relevant sticky trap densities (1/170 m², cf. above) and validation is in progress.

# Conclusions

Yellow sticky traps provide far more information than only detection of pest presence. They provide quantitative data on pest population development, which already indicates to a certain degree success and failure of plant protection measures. Therefore, yellow sticky traps comprise a valuable tool for reliable monitoring of the economic threshold throughout the season. Additionally, they offer quantitative data on the establishment and therefore successful use of natural enemies. This is at least true for *E. formosa* but most likely also for many other beneficials attracted to coloured sticky traps. Based on natural enemy population density growers might decide to terminate release of natural enemies and save money. Trap densities in the greenhouse needed for reliable estimation of pest density, i.e. 1-2 traps / 200 m², are in accordance with actual practice. Results will be integrated in a decision support system and in particular the reliability of the correlation of adults on traps with nymphs on plants the previous week will be confirmed in commercial greenhouses.

Since identification and counting of natural enemies on large numbers of yellow traps is labour intensive (at least for inexperienced growers) automated monitoring devices, like for instace the Scoutbox®, are needed. Equipped with object recognition algorithms they will also reduce the error due to misidentification when several people are responsible for plant protection decisions. Whether a (semi-) automatic or even visual inspection of yellow sticky cards for optimization of beneficial introduction regime is acceptable for growers and pays off economically remains to be investigated.

# Chapter 2

## Sticky trap monitoring of a pest-predator system in greenhouse tomato crop – are commercially available trap colours sufficient?

## Abstract

Monitoring of pest presence and population development in the crop during the season is essential for integrated pest management. Although many tools, for instance coloured sticky traps, have been developed the full advantage of available information is rarely taken into account in decision making. The reasons behind include high workload in practice but also the poorly studied relationships between trap catches and populations in the crop. Here we investigate if commercially available coloured sticky traps can be used as tool to monitor population densities of a pest-predator system in greenhouse tomato. The response of *Macrolophus pygmaeus* Rambur (Hemiptera, Miridae) to blue and yellow sticky traps was tested in lab and greenhouse experiments. The results indicate that *M. pygmaeus* can be monitored equally well with both colours and that the number of trapped insects showed good correlation with the population densities on the crop. Under growing conditions, more *M. pygmaeus* were trapped on blue compared to yellow sticky traps. However, due to the known preference of *Trialeurodes vaporariorum* Westwood (Hemiptera, Aleyrodidae), yellow traps should be preferred for a combined pest-predator monitoring.

**Key words:** Population development, *Macrolophus pygmaeus*, Miridae, *Trialeurodes vaporariorum,* Aleyrodidae, tomato, sticky trap

# Introduction

The use of beneficial arthropods nowadays has become a standard tool in protected horticulture (van Lenteren, 2000; Pinto-Zevallos and Vänninen, 2013). Commercially used arthropods include pollinators and natural enemies, such as parasitoids and predators. With the exception of predatory mites, most natural enemies pass alate developmental stages which allows for fast dispersal and efficient location of the target pest. Moreover the specific response of many flying insects to trapping devices make them ideal candidates for continuous population monitoring (Webb et al., 1985). But although the use of natural enemies has become standard, their monitoring remains underrepresented in literature and practice, as compared to pest species. The reason for this is unclear, because in integrated pest management (IPM) the monitoring of pests and beneficials is the precondition for optimal decision making as basis for management actions in pest control (Binns and Nyrop, 1992). Recently, two studies included parasitoids in existing monitoring schemes of *Bemisia tabaci* to enhance informative value (Qiu and Shunxiang, 2006; Hoelmer and Simmons, 2008).

In general monitoring is time consuming and therefore several facilitation tools, i.e. coloured sticky traps, pheromone traps and suction traps, were developed. Due to the attractiveness of specific wavelengths for many insects, coloured sticky traps became a key component in IPM programmes for flying pests in many crop, especially in protected agriculture (Steiner et al., 1999; Pinto-Zevallos and Vänninen, 2013). The advantage of insect counts on sticky traps compared to counts on crop plants can be threefold as they are (1) cost efficient and easy to use, (2) effective in detection of first pest occurrence (Natwick et al., 2007) and (3) require lower handling time (Pizzol et al., 2010). However, depending on the trap density needed for accurate estimation and the number of trapped insects that need to be counted, traps are not always the most efficient monitoring technique (Naranjo et al., 1995). Manual handling of traps and proper identification are most likely the limiting factors for many growers, but currently, automatic counting and identification of trapped insects is fostered (Guarnieri et al., 2012; Xia, 2012) and first products, e.g. scoutbox ® (Cropwatch, Wageningen, The Netherlands) and trapview® (EFOS d.o.o., Hruševje, Slowenia), are available on the market. Such automation potentially leads to reduced workload for growers in the near future, increase reliability and adds further to the application of sticky traps in practice.

Whenever a pest and its natural enemy can be monitored with the same trap, a conclusive picture about the status of pest control in the crop can be drawn with reasonable workload. However, before the full information content of sticky traps can be used in decision making, the relationship between trap catches and population development has to be characterised for each tritrophic system of pest - beneficial - crop. The majority of users apply sticky traps without knowledge of monitoring validity for actual pest or beneficial densities on crops. Nevertheless, meaningful correlations of trapped insects with population densities in the crop were described already for thrips, whiteflies and parasitoids (Gerling and Horowitz, 1984; Macintyre-Allen et al., 2005; Böckmann et al., 2014). But there are also examples with parasitoids and whiteflies, where no such correlation could be recognised so far (Karut and Kazak, 2007; Hoelmer and Simmons, 2008) or where correlation was only valid in the close proximity of traps (Gillespie and Quiring, 1987).

High selectivity and strong attraction of coloured traps is a requirement for mass trapping and an advantage for monitoring of pests. Low selectivity of coloured traps on the other hand is often regarded as a drawback, due to by-catch of non-target insects. Therefore, for pest monitoring, the main criteria for selection and optimisation of sticky traps are the colour preferences of the target insect (Hoback et al., 1999; Döring et al., 2012; Sétamou et al., 2014) and attractivity can for instance be increased by adding additional olfactory cues. From an evolutionary point of view orientation to specific colours and volatiles is common for most pollinators due to their coevolution with flowering plants (Chittka and Menzel, 1992). Among them are important groups of Hymenopteran and Dipteran beneficials which cover their nutritional needs with pollen and nectar (Wäckers et al., 2005). Accordingly, many natural enemies are regularly found on coloured sticky traps (Hoelmer and Simmons, 2008; Larsen et al., 2014). Especially yellow is attractive to a wide range of insects, whilst blue is mainly known to be attractive for *Frankliniella occidentalis,* other thrips species, and hoverflies (Hoback et al., 1999; Johansen et al., 2011). In contrast to monitoring of pests, too strong attraction of natural enemies to sticky traps is not desirable in order to conserve populations on the crop. However, some attraction is needed to monitor their successful establishment, i.e. their occurrence in sufficient high levels in relation to the pest to provide effective control. Focussing on their establishment, the monitoring approach for beneficials is therefore different as compared to pest monitoring, were low population densities must be detected to introduce beneficials timely.

A well-documented example in greenhouse tomato crops is the whitefly *Trialeurodes vaporariorum* Westwood (Hemiptera, Aleyrodidae), a major pest that is frequently monitored with yellow sticky traps. These traps show high attractivity for *T. vaporariorum*, enabling early pest detection in the crop (Gillespie and Quiring, 1987) and monitoring of population development throughout the season (Kim et al., 2001; Böckmann et al., 2014). In several studies it was shown that attraction to yellow sticky traps was highest as compared to any other trap colour or trap plant tested (Webb et al., 1985; Moreau and Isman, 2011). Also, the simplicity of the technique supported fast development and adoption in practice. Control of greenhouse whitefly mainly relies on the introduction of beneficials and the standard procedure in year-round tomato cultures are preventive introductions of *Macrolophus pygmaeus* Rambur (Hemiptera, Miridae) shortly after planting of the crop. In practice, the detection of 5 *M. pygmaeus* of any developmental stage per plant is used as an indicator for establishment of the beneficial (Theo Reintges, LWK North Rhine-Westphalia; Markus Knapp, Koppert B.V.; personal communication). Because establishment of *M. pygmaeus* takes typically about 8-10 weeks, control during that period is often assured by additional repeated introductions of *E. formosa* (Hymenoptera: Aphelinidae). Both most important natural enemies of *T. vaporariorum*, i.e. *Encarsia formosa* and *M. pygmaeus*, are alate and therefore can potentially also be trapped on sticky traps. For several parasitoids, the attraction to coloured sticky traps is documented in literature (Sheble and Kozar, 1995; Romeis et al., 1998; Scholler and Prozell, 2003). For *E. formosa*, parasitism rates were highly correlated with number of parasitoids caught on yellow traps (Böckmann et al., 2014). Although it is known from the literature that prey finding of *M. pygmaeus* most likely depends primarily on olfactory and not on visual cues (Freund and Olmstead, 2000), adult predatory bugs can be found frequently on both, i.e. blue and yellow traps (personal observation).

In this study, we investigate the hypothesis that *M. pygmaeus* responds indifferently to blue and yellow sticky traps, the most commonly used trap colours in protected crop. Furthermore, we analyse if population densities of

*M. pygmaeus* on tomato crop in commercial greenhouses correlate with adult trap catch.

# Methods

## Experimental setup

### *Colour attraction of M. pygmaeus*

To clarify the importance of colour for orientation in *M. pygmaeus*, choice experiments in gauze cages (25 cm length x 15 cm width x 15 cm height) were carried out in June / July 2014. Cages were covered on top with green cardboard to simulate the crop habitat. Adult *M. pygmaeus* were purchased from Katz Biotech AG, Baruth, Germany. Sex ratio of the insects was about 2:1 in favour of females and experiments were carried out without further sex determination. The insects were stored individually in small glass tubes in dark conditions in a climate chamber (24°C, 60 % RH) for 24 hours without food supply prior to experimental use. A moist cotton pad was added to each tube. Afterwards a single insect was introduced in the centre of the gauze cage. In choice experiments, a coloured sticky trap (blue or yellow, Horiver®, Koppert B.V., Berkel en Rodenrijs, The Netherlands) was offered in combination with the second colour or with a transparent Plexiglas trap covered with insect glue (Temmen Insekten-Leim, Temmen GmbH, Hattersheim, Germany). Therefore, two traps at a time were presented simultaneously at the same side of the cage. Size of all traps was 7.5 x 7.5 cm. Position of traps was randomized for each run and insects were observed for a maximum of 90 min. Experiments were scored every 5 min and capture time of insects was noted. For each combination, 40 replicates were realised daily from 10 am to 16 pm.

Additionally, the attraction to the trap as compared to the attraction to tomato leaves was investigated for yellow sticky traps only. For this experiment, the setup remained as described, but a Plexiglas disc of 7.5 x 7.5 cm was entirely covered with tomato leaves (cultivation Campari F1, Enza Zaden, Enkhuizen, The Netherlands), which were then covered with insect glue. For this experiment 30 replicates were carried out under greenhouse conditions with artificial lighting from top (sodium vapour lamps) and mean temperatures of 26.5 ± 3.6°C (mean ± SD).

Additionally, colour preferences and correlation of trapped insects with counts on plants were investigated under standard growing conditions. Therefore a 170 m² experimental glasshouse was prepared with 260 tomato plants (grape tomato, cultivar: Campari; Enza Zaden Deutschland GmbH & Co. KG) in 6 single rows. In this greenhouse, plants were allowed to grow up to 2.5 m and shoot tips were cut thereafter. Growing period was from calendar week 17 to 39 in 2013. *T. vaporariorum* was introduced on 5th of June 2013 with 30 individuals at two distinct locations. Individuals originated from a permanent rearing on tobacco plants (Leibniz Universität Hannover, Institute of Horticultural Production Systems, Germany). All beneficials were purchased and distributed according to instructions for commercial greenhouses (see next paragraph). Introduction dates and densities of natural enemies, i.e. *M. pygmaeus* and *E. formosa* are shown in Figure 1. *Sitrotoga* sp. eggs were supplied (3*50 g / ha / 14 d) as additional food source on introduction sites of *M. pygmaeus*. Blue and yellow sticky traps were distributed equidistant at a regular grid with 1 trap / 43 m² (Horiver® / Horiver®-TR., Koppert B.V., Berkel en Rodenrijs, The Netherlands), resulting in a total of 4 traps of each colour. Trap size was 25 cm (length) by 10 cm (width). Position of traps was adjusted to height of the growing tips until maximum plant height was reached. Additionally 16 tomato plants on a regular grid were monitored. On the crop, whiteflies (adults and nymphs), *M. pygmaeus* (adults and nymphs) and *E. formosa* (black whitefly nymphs) were counted. Due to the high sampling effort for monitoring in this large scale experiment, only whitefly nymphal instars which were easily detectable by the naked eye were included, namely the 3rd and 4th instars. Counts were taken from 3 leaves at lower, intermediate and upper plant level, i.e. 9 leaves per plant in total. Monitoring on plants and traps was carried out weekly. In calendar week 30, application of Vertimec® (Syngenta, active ingredient: 18 g / l Abamectin, application rate: 1.2 l / ha) became necessary on one third of the crop, due to infestation with *Aculops lycopersici*. Temperature was measured in 10 min intervals throughout experiment and average temperature including all measures was 21.3 ± 3.6°C (mean ± SD).

### *Monitoring of M. pygmaeus and T. vaporariorum* in commercial greenhouses

Experiments were carried out in three commercial tomato greenhouses, i.e. one heated glasshouse and two unheated poly-tunnel. The commercial glasshouse of 780 m² contained 1400 tomato plants of different cultivars (cocktail tomato, grape tomato and beef tomato) in 5 double rows. Plants were vertically grown to maximum height of 3.2 m, were then laid down by approximately 30 cm while the position was gradually shifted sideways using tomato hooks. At another commercial grower, two poly-tunnels (commercial poly-tunnel-1 and commercial poly-tunnel-2) with several cultivars of grape tomato were monitored. Both poly-tunnel contained 520 plants in 4 double rows on 300 m². Plants were grown to maximum height of 1.9 m in an angle of 60° and then the position was gradually shifted sideward using tomato hooks. Growing period in 2013 was from calendar week 10 to 43 in the commercial glasshouse and from 13 to 38 in both commercial poly-tunnel. In both tunnel, a treatment with Neudosan® Neu (Neudorff, active ingredient 515 g / l potassium salts from natural fatty acids; application rate: 18 l / ha) was carried out at calendar week 16 in order to reduce initial aphid infestation. Additionally to *M. pygmaeus*, also *E. formosa* was introduced at the beginning of the season to ensure control of *T. vaporariorum*. In case of the commercial glasshouse, the grower decided for additional parasitoid introductions in July / August due to (relatively) high whitefly densities. Dates of natural enemy introductions and densities are indicated in Figure 2. *E. formosa* was supplied as black (i.e. parasitized) nymphs on paper cards that were clipped to plants at regular distributed locations within the greenhouses. *M. pygmaeus* was supplied in plastic boxes on paper strips, containing a mixture of adults and late nymphs. Paper strips were divided into clusters containing approximately 25 insects and placed on plants at regular distributed locations. As supplementary food source, *Sitotroga spp.* eggs were distributed with about 170 g / ha on plants at introduction sites of *M. pygmaeus*, once after each introduction. In all commercial crops natural immigration of the pest was awaited. Beneficials for all cultures were purchased from Katz Biotech AG (Baruth, Germany).

Yellow sticky traps (Horiver®, Koppert B.V., Berkel en Rodenrijs, The Netherlands) were used at density of 1 trap / 130 m² in the commercial glasshouse (6 traps in total) and 1 trap / 100 m² in the commercial poly-tunnel 1 and 2 (3 traps per tunnel). Trap size was 25 cm (length) by 10 cm (width). Position of traps was adjusted in height to top of the crop until maximum plant height was reached. Traps were either renewed, or all target insects were removed from traps, after counting.

Adult *T. vaporariorum*, *M. pygmaeus* and *E. formosa* were counted fortnightly on all sticky traps. On the crop, whiteflies (adults and nymphs), *M. pygmaeus* (adults and nymphs) and *E. formosa* (black whitefly nymphs) were counted. Due to the high sampling effort for monitoring in these large scale experiments, only whitefly nymphal instars that were easily detectable by the naked eye were included, namely the 3rd and 4th instars. Counts were taken from 3 leaves at lower, intermediate and upper plant level, i.e. 9 leaves per plant in total. In the commercial glasshouse 12 and in each commercial poly-tunnel 6 plants, positioned on a regular grid, were sampled. Temperature was measured in 10 min intervals throughout experiments and average temperatures including all measures were 19.5 ± 4.6°C (mean ± SD) in the commercial glasshouse, 20.9 ± 5.9°C in the commercial poly-tunnel-1 and 20.2 ± 5.7°C in the commercial poly-tunnel-2. Temperature differences over the growing period were on average below 2°C for all cultures with higher variability in the commercial poly-tunnel than in the glasshouses.

## Statistical analysis

### *Colour preference of M. pygmaeus*

Choice experiments carried out in gauze cages were analysed using the Chi-square test (goodness of fit). A distribution of 1:1 was expected for each experiment. Only individuals that were trapped after 90 min were included in the analyses.

For the greenhouse experiment with blue and yellow sticky traps presented at equidistant positions, numbers of *M. pygmaeus* adults caught on yellow and blue traps, respectively, were summed up for each trap over all sample dates. Comparison of sums was done with Wilcoxon rank test.

### *Monitoring of M. pygmaeus and T. vaporariorum*

First, linear models were fitted for each trap colour in the experimental glasshouse, in order to select a suitable colour for beneficial monitoring at commercial greenhouse scales. Then, linear models for the use of yellow sticky traps were fitted using the count data of all commercial greenhouses, in order to establish universally valid models. For each sampling date, the average of counts on traps and plants was calculated per greenhouse. Averages were based on all sampled plants (i.e. sum of counts on 9 leaves per plant) or traps sampled in the respective greenhouse. Prior to analysis, data of all commercial greenhouses were combined and were ln (x + 1) transformed. Because the calculated linear models should later be used to predict insect densities on plants by trap catch, numbers of adults on traps were used as explanatory variable in all models. For *M. pygmaeus* and *T. vaporariorum*, adult or nymph counts on plants were used as dependent variable. Because in practice the total number of *M. pygmaeus* adults and nymphs is usually counted together to estimate establishment of the beneficial, additional models were fitted using the summed values of both stages of the predatory bug.

Trap catches and parasitism rates of *E. formosa* were very low and consequently no models were fitted for the parasitoid. All analyses were carried out with the statistical software R (version 3.1.2).

# Results

## Colour preference of *M. pygmaeus*

Soon after introduction into the cage, adults of *M. pygmaeus* moved actively and showed directed flight towards sticky traps. Between 67.5 % (blue vs. transparent trap) and 86.7 % (yellow trap vs. tomato leaves) of the insects were trapped on one of the sticky traps within a 90 min time interval; 94 % of them were caught within the first 45 min. When only one colour at a time was presented to single *M. pygmaeus* adults, yellow sticky traps were 2-times more attractive than transparent traps ($\chi^2 = 4.48$, N = 27, df = 1, p = 0.03) whereas such difference was not found for blue traps ($\chi^2 = 1.20$, N = 30, df = 1, p = 0.27) (Figure 3). When adults had the choice between blue and yellow traps, no colour was preferred ($\chi^2 = 0.27$, N = 33, df = 1, p = 0.60). Additionally, yellow sticky traps and tomato leaf coated traps were similar attractive for *M. pygmaeus* ($\chi^2 = 0.62$, N = 26, df = 1, p = 0.60) (Figure 1).

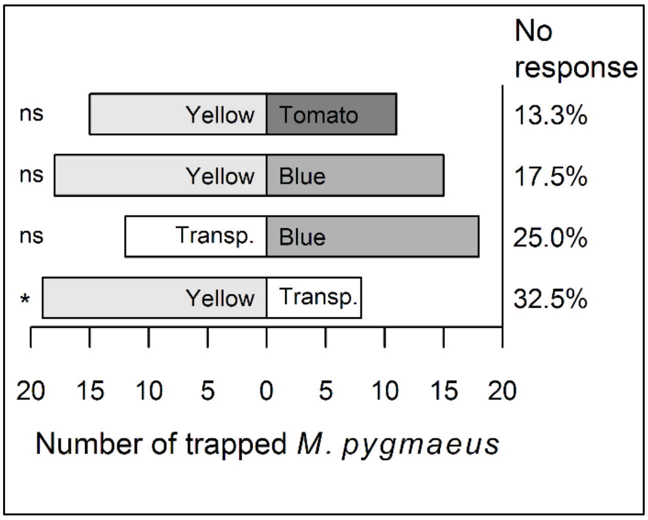

**Figure 1** Preference of adult *M. pygmaeus* for either blue, yellow, transparent or a sticky trap covered with tomato leaves. Insects were released individually and results cover directed flight to one of the targets within a 90 min observational interval. Proportions of insects that did not react during that time are given on the left hand (no response) (n = 30-40). Statistical comparison was done with Chi-square-test. A significant difference was only found for the yellow compared to transparent trap. Detailed statistics are shown in the text.

When blue and yellow sticky traps were simultaneously hung in the experimental glasshouse, *M. pygmaeus* was found regularly on both trap types. Throughout the season 27 ± 12.9 and 44 ± 14 (sum per trap ± SD) adults were caught per yellow and blue trap, respectively, but differences were not significant (Wilcoxon rank test, N = 4, p = 0.20). In contrast, throughout the season on average 379 ± 22 (sum per trap ± SD) adult whiteflies were caught on yellow and only 7 ± 5 (sum per trap ± SD) on blue traps (Wilcoxon rank test, N = 4, p = 0.03) (Figure 2).

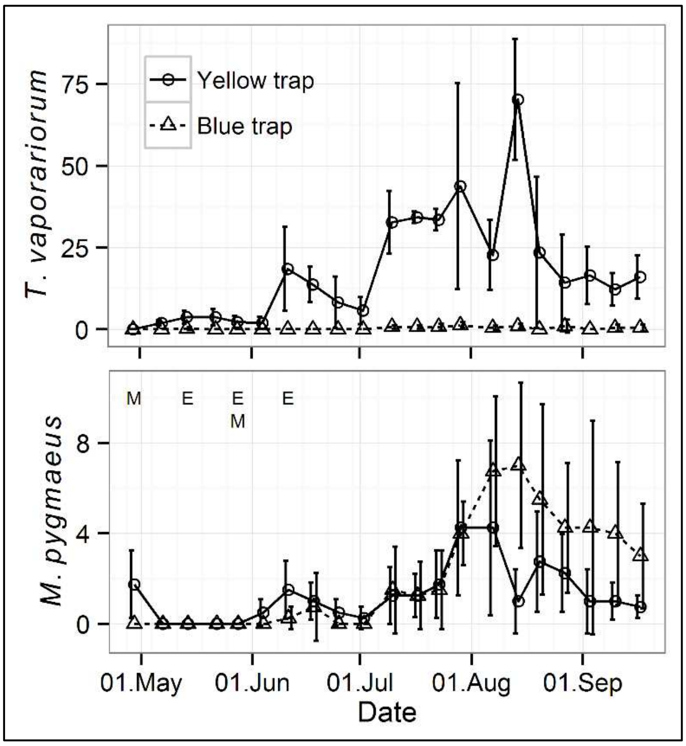

**Figure 2** Average number of *M. pygmaeus* and *T. vaporariorum* caught on blue or yellow traps in the experimental glasshouse throughout the season. The values (mean ± SD, N = 4) are based on data of 4 traps for each colour, hanging equidistant on a regular grid in the experimental glasshouse. Introductions of *M. pygmaeus* (1.2 / m²) and *E. formosa* (3 / m²) are dated by their initial letters.

Using blue and yellow trap catches from the experimental glasshouse as explanatory variable, linear models were fitted using nymphal- and adult counts and using counts of both stages together on plants as dependent variable. Correlations were significant for both trap colours with $R^2 \geq 0.42$ but explained variance was always higher for blue as compared to yellow trap catches (Figure 3).

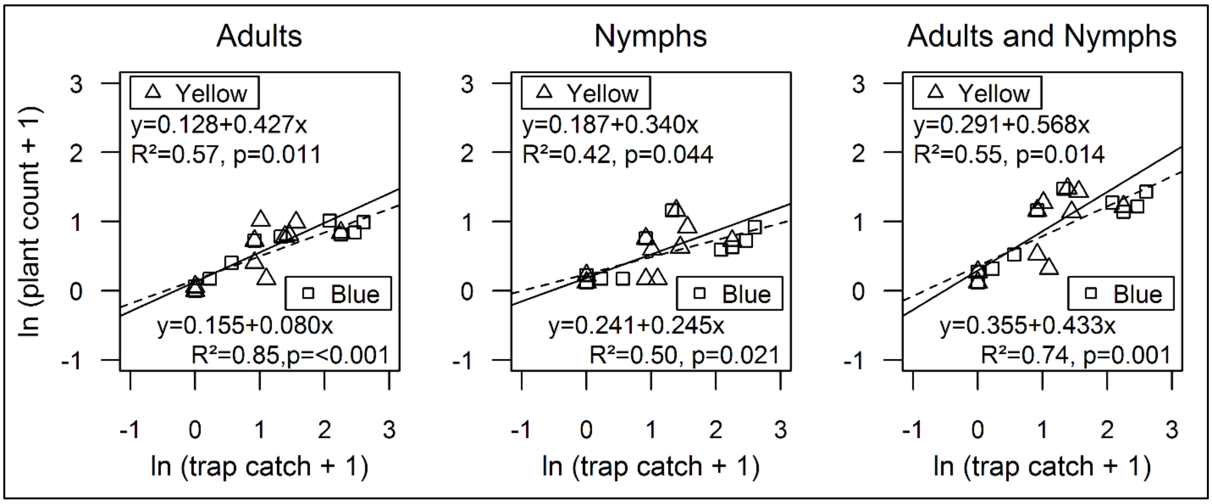

**Figure 3** Linear regression models to investigate correlation between yellow- (solid line) and blue trap catches (dashed line), respectively of adult *M. pygmaeus*, and densities of its different developmental stages on the tomato crop. All models were fitted based on data collected at the experimental glasshouse. Data points refer to mean values of all plant- (i.e. sum of 9 leaves per plant) or trap counts calculated separately for every sampling date. Data was ln (x + 1) transformed prior to analyses.

## Monitoring of *M. pygmaeus* population development

*M. pygmaeus* was released the first time in April but populations remained low until the beginning of June in all greenhouses. Effects of treatments with the insecticide Neudosan Neu® in calendar week 16 were not detectable due to the very low density of the beneficial at application time. Nymphal and adult numbers on crop increased until end of July and numbers remained at high level in all locations (Figure 4). Comparing the different locations, the overall highest nymphal density was reached in the commercial glasshouse with an average of 4.2 nymphs per leaf. Highest adult density on plants was reached in the poly-tunnel-1 with an average of 1.5 adults per leaf. The same is true for the maximum trap catch in two weeks, with an average of 27.7 adults per trap.

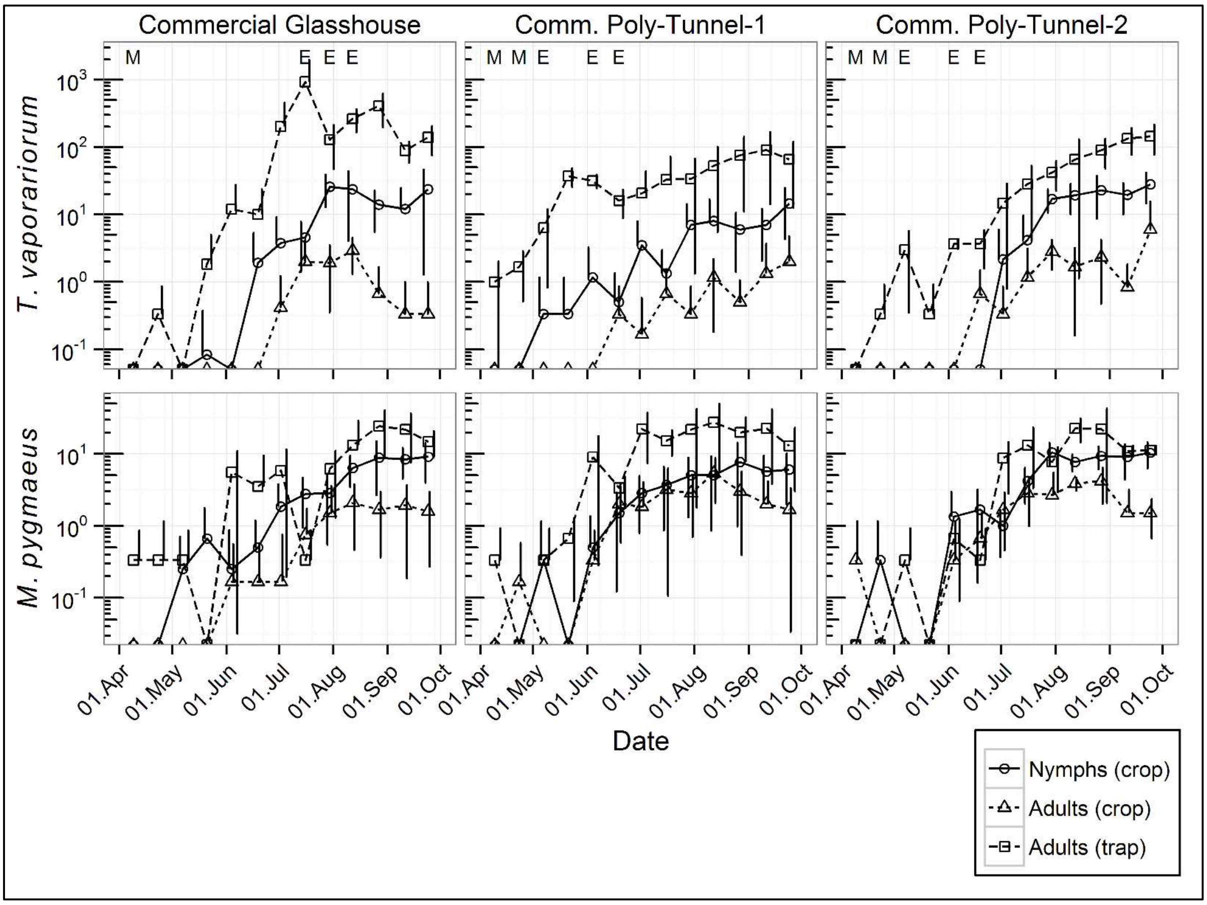

**Figure 4** Population development of *M. pygmaeus* and *T. vaporariorum* on crop and yellow sticky trap catch. Adult and nymph numbers on crop refer to average count per plant (i.e. sum of counts from 9 leaves) from 12 plants (commercial glasshouse) or 6 plants (commercial poly-tunnel-1, commercial poly-tunnel-2). Adult trap catches refer to average count per trap from 6 traps (commercial glasshouse, experimental glasshouse) or 3 traps (commercial poly-tunnel-1, commercial poly-tunnel-2). Data are shown on logarithmic scale with 0-values clipped to the x-axis. Standard deviations reaching below zero were omitted. Introductions of *M. pygmaeus* (0.5 / $m^2$ in the commercial glasshouse; 1 / $m^2$ in both commercial poly-tunnel) and *E. formosa* (6.4 / $m^2$ in the commercial glasshouse; 5 / $m^2$ in both commercial poly-tunnel) are dated by their initial letters. Note that in the commercial tunnel one additional introduction of *M. pygmaeus* (0.5 / $m^2$) and *E. formosa* (4.5 / $m^2$) was carried out at March 14.

Scatter plots showed similar data distributions in all commercial greenhouses with yellow trap catch of adults as explanatory variable and nymph, adult or nymph + adult numbers on crop as dependent variable (Figure 5A). Consequently, a single linear model for each dependent variable was fitted, combining the data of all commercial greenhouses. All models were highly significant for all dependent variables with $R^2$-values ranging between 0.70 – 0.75 (Figure 5A).

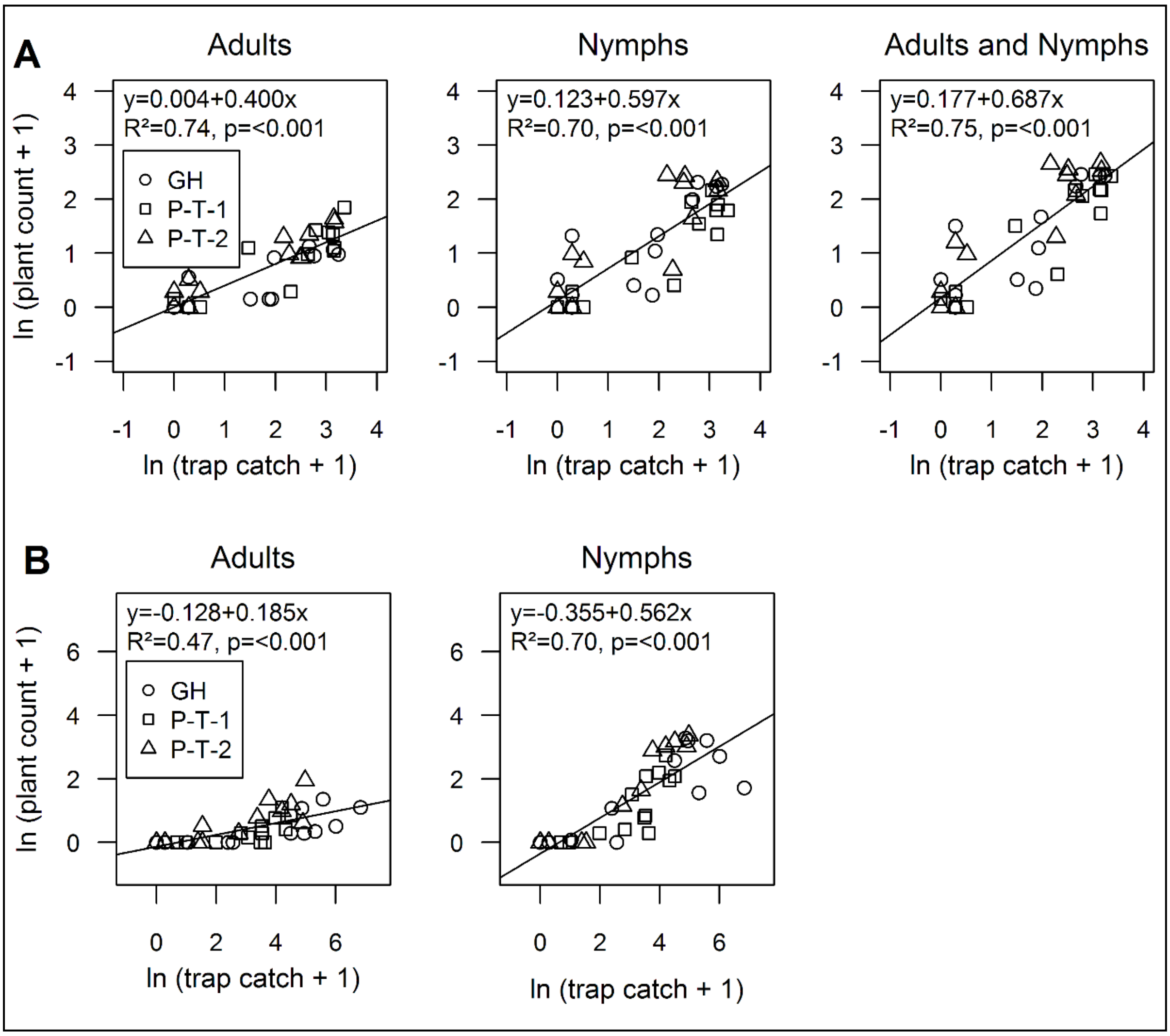

**Figure 5** Linear regression models to investigate correlation between yellow trap catches of adult *M. pygmaeus* **(A)** or *T. vaporariorum* **(B)** and densities of different developmental stages of the respective insect on the crop. All models were fitted based on data collected in all commercial greenhouses (commercial glasshouse = GH, commercial poly-tunnel-1 = P-T-1, commercial poly-tunnel-2 = P-T-2). Data points refer to mean values of all plant- (i.e. sum of 9 leaves per plant) or trap counts calculated separately for every sampling date and location. Data was ln (x + 1) transformed prior to analyses.

## Monitoring of *T. vaporariorum* population development

Whitefly population remained low until June in all greenhouses. Throughout the season adult counts remained low as compared to nymphs. Due to these low densities, effects of treatment with the insecticide Neudosan Neu® in calendar week 16 in both poly-tunnel were not detectable. In the commercial glasshouse a pronounced peak in the population development can be identified within the season from mid-July to mid-August. In both commercial poly-tunnels nymphal and adult *T. vaporariorum* populations increased moderately throughout season without reaching a distinct population peak (Figure 4).

Highest nymphal numbers were reached in the commercial glasshouse with an average of 2.9 nymphs per leaf and highest adult numbers were reached in the commercial poly-tunnel-2 with an average of 0.7 adults per leaf. Maximum trap catch of adult whiteflies was recorded in the commercial glasshouse with an average of 930.7 adults per trap caught in two weeks.

Scatter plots showed similar distributions for data of all commercial greenhouses with adult yellow trap catches as explanatory variable and nymphs or adult numbers on crop as dependent variable (Figure B). Consequently, single linear models were fitted for each dependent variable, combining the data of all commercial greenhouses. Significant models using adult trap catches as explanatory variable could be fitted for nymph and adult counts on plants as dependent variable (Figure 5B). Nevertheless proportion of variation explained by the models was almost 1.5 – fold increased for nymphal as compared to adult counts on plants.

# Discussion

## Colour preference of *M. pygmaeus*

*M. pygmaeus* did not prefer one of the tested trap colours, but shows a distinct preference for coloured traps compared to transparent ones. Because flight activity was also directed to transparent traps it is likely that shape provides additional information for orientated flights. Contrasting contours and light blue shimmering of Plexiglas may have affected the orientation to transparent traps and potentially obscured a difference between the blue and the transparent trap. That shape might play a major role is also supported by the fact that diurnal, crepuscular and also nocturnal flight activity was frequently observed in different species of the family Miridae (Heteroptera) to which *M. pygmaeus* belongs (Blackmer et al., 2004). Although *M. pygmaeus* is actively walking on plants and flying in greenhouses at daytime (personal observation), Perdikis et al. (2004) observed that adults and late instars *M. pygmaeus* mainly hunt in the dark. Other authors also assume that mating takes place at night times (Gemeno et al., 2007). Therefore it is likely that to some extent, *M. pygmaeus* trap catches in the greenhouse take place during flights at crepuscular light or night times, but further studies are needed to confirm this hypothesis. In general colour vision in nocturnal insects is much scarcer than in diurnal ones. However, some hawk moths and some large bees and grasshoppers may have adapted to nocturnal colour vision (Kelber and Roth, 2006). Nevertheless it seems to be unlikely that *M. pygmaeus* uses colour vision during night times because this predator is quite small and not exclusively nocturnal. Furthermore, our experiments have shown that a yellow trap is not of higher attractiveness compared to a similar sized green leaf area at daytime (Figure 1). The lower or absent attraction of *M. pygmaeus* to yellow traps is clearly visible when comparing the numbers caught per trap of the predatory bug and *T. vaporariorum* (Figure 2). The high attraction of *T. vaporariorum* to yellow is known (Webb et al., 1985; Moreau and Isman, 2011) and was also significant in the current study. Moreover, the maximum trap catch on a single yellow trap was with 91 whiteflies was about 9 times higher as compared to *M. pygmaeus* (10 individuals), whilst the maximum number of whiteflies on a blue trap was with 4 individuals half of the number of trapped predatory bugs (11 individuals) (Figure 2). Hence, we found a more balanced number comparing trap types, and much lower numbers in total. However, in our greenhouse experiments there seems to be a trend that more *M. pygmaeus* were found on blue traps as compared to yellow traps towards the end of the season (Figure 2). This result is in contrast to the results of our choice-experiment, where *M. pygmaeus* was equally attracted to both trap types (Figure 1). Most natural enemies show a preference to yellow coloured traps (Dowell and Cherry, 1981; Udayagiri et al., 1997; Beers, 2012). In fact, very few insect species prefer blue colour, for instance some thrips and hoverflies (Hoback et al., 1999; Johansen et al., 2011). Comparing traps of white, blue and yellow colour in field plots of different rice cultivars the predatory bug *Orius similis* was most attracted to yellow (Raen et al., 2013). Furthermore, the least *O. similis* adults were found all times on blue traps, but the authors did not check for significance in those differences. In both genera, *Orius* and *Macrolophus*, the visit of flowers and the use of pollen as food source are known (Ishida et al., 2009; Maselou et al., 2014), but both genera show omnivorous feeding habits (Hillert et al., 2002; Pumarino and Alomar, 2012) and are active at day and night times (Askari and Stern, 1972; Hamdan, 2006). However, our data supports the assumption that *M. pygmaeus* reacts rather unspecific to colour (Figure 1 and Figure 2). Because in tomato crops colour of flowers or prey is not very prominent, it is likely that the predatory bug uses mainly the contours of plants or leaves for orientation during flight activity. Hence, for our glasshouse experiment, were traps are placed within crop, it is likely that the trap that is most similar to a tomato leave is preferred. The wavelength of yellow traps is with 550-700 nm quite similar to fresh leaves (light green), whereas blue traps with 400-500 nm are similar to older leaves (dark green) (Natwick et al., 2007). Because plant tips were cut in the experimental glasshouse in June, few fresh leaves where left in late summer. Hence the general appearance of plants was more similar to the blue traps (i.e. darker), which may have caused the increase of trap catches on blue as compared to yellow traps at that time. Such difference would not have been detected in the choice experiments, were traps were presented in front of a white background. Studies of colour preference of *M. pygmaeus* are at their beginning, and consequently the current study raises many new questions. To get a more complete picture of colour attraction of this predatory bug, further studies should also test difference in colour attraction due to habituation, at different time of the year, between sexes and also include seasonal shifts. However, our data show that there is no strong attraction to blue or yellow traps. Therefore and keeping in mind the low density of yellow traps used in practice and in the present study, an influence of this monitoring technique on the population development of the predator in commercial greenhouses, i.e. unwanted mass trapping, can be neglected.

For monitoring of natural enemies in practice, it remains most important that correlations of trap catch with population densities on the crop are meaningful. Such correlations were more accurate for blue as compared to yellow traps (Figure 3). Still, correlations for both trap types explained always more than 40 % of the variance of *M. pygmaeus* nymphs and adults monitored on plants. Correlation of trap catches with total number of adults and nymphs on plants explained 74 % of the variance for blue and 55 % for yellow traps. In tomato, *M. pygmaeus* is mainly used to control *T. vaporariorum.* Because this pest is commonly monitored with yellow traps, it is most cost and time saving to monitor both, *T. vaporariorum* and *M. pygmaeus* on the same trap type.

## Monitoring of *M. pygmaeus* in the crop

It was tested if yellow traps can be used for a comprehensive monitoring of *M. pygmaeus* population densities in commercial greenhouses using practice relevant trap densities. For practical considerations, we used 1 trap per 100-200 m², a density that we confirmed earlier already for whitefly monitoring in tomato (Böckmann et al., 2014). Under these conditions, no structural differences were detected in scatterplots for the relation between plant and trap counts between the 3 commercial greenhouses (Figure 5A). Therefore it was possible to combine data of all commercial greenhouses for model evaluation. On this basis, explanation of adult numbers on crop was more accurate than for nymph numbers (74 % vs 70 % of variance explained by the model). The latter was expected because only adult predatory bugs are alate and therefore directly correlated with trap catch. In contrast, nymph counts on plants correlate indirectly with adult trap catch due to their (supposed) direct correlation with adult counts on plants. Considering that the restriction to monitoring of mobile, alate developmental stages is considered as a major drawback of sticky traps (Musser et al., 2004), the accuracy of the indirect correlation with *M. pygmaeus* nymphs is surprising. However, similar good correlations between nymphs and adult trap catch were also found for whiteflies (Kim et al., 1999; Böckmann et al., 2014).

Generally little attention is spend so far on sampling to predict biological control (Nyrop and Vanderwerf, 1994). Nevertheless, many natural enemies can be found on sticky traps (Dowell and Cherry, 1981; Udayagiri et al., 1997; Beers, 2012). To our knowledge, monitoring of predatory bugs to date is mainly based on direct counts on the crop (Isenhour and Yeargan, 1981; Elkassabany et al., 1996). Monitoring of predatory bugs with sticky traps has the potential to reduce workload and costs (Musser et al., 2004). Although the concept of economical thresholds was not designed for predators, this classification may be suitable for predator sampling to predict biological control (Musser et al., 2004). One possibility to classify biological control impact is the predator / prey ratio (Nyrop and Vanderwerf, 1994). This classification is of limited use when it comes to generalist predators, which exploit a range of food sources and do not depend on single pests. Therefore Musser et al. (2004) propose to classify populations of a generalist predator and its primary prey as being large or small, in order to reduce sample effort. This threshold based concept, which we also used as basis for our decision support software

(Böckmann and Meyhöfer, 2014), fits perfectly the needs for assessment of *M. pygmaeus* in greenhouse tomato. Growers consider already two population levels to be relevant: The first level is between 3 and 7 *M. pygmaeus* per tomato plant, indicating the establishment of the predatory bug in the crop (personal communication Markus Knapp, Koppert B.V., Joke de Jong, SoilCares Research). Estimation of that level can be used to optimise decision making in different ways. If, for instance, *E. formosa* is introduced to control *T. vaporariorum* in the early season, introductions can be stopped once *M. pygmaeus* became established. Also if *E. formosa* is not introduced, a good estimation of the population build-up of *M. pygmaeus* is needed to decide if additional control measures have to be taken, once *T. vaporariorum* is detected. The latter is to some degree also true for the detection of aphids or spider mites, which are also attacked by *M. pygmaeus*. The second level that some growers consider is the threshold of 10 *M. pygmaeus* per plant, at which the predatory bug is regarded to cause plant damage (personal communication Joke de Jong). This grower's threshold is however not in line with results on tomato crop damage mentioned in literature. Here, damage is mainly considered to occur at very high predator densities and low prey availability under experimental conditions (Castañé et al., 2011). Only a single study by Sampson and Jacobson (1999) reported distorted tomato leaf growth, necrotic spots on leaves and scars on fruit in a UK field survey at predator densities of 50–300 individuals per plant and low prey abundance.

Because growers do not distinguish between *M. pygmaeus* nymph- and adult stages on the plant to estimate population densities, a model that predicts the density of mixed populations would be most relevant to assess the earlier mentioned thresholds in practice. In our experiments, trap catches explained 75 % of the variance of *M. pygmaeus* mixed population on the crop (Figure 5A). This correlation model has therefore high potential for application to yellow trap monitoring in commercial tomato glasshouses and poly-tunnels in the temperate climate zone. As mentioned before such monitoring will not incur additional material costs, assuming that *T. vaporariorum* is already monitored with yellow traps. Also additional monitoring time would be moderate, because *M. pygmaeus* can be easily identified with the naked eye, and is usually trapped in moderate numbers. For instance, total numbers per trap never exceeded 40 insects in the current study.

Research on correlations of trap catch and population densities on plants is ongoing for *M. pygmaeus*, to validate the accuracy of predictions on predator densities based on the current results. Because *M. pygmaeus* also feeds on thrips, aphids and spider mites (Perdikis and Lykouressis, 2000; Blaeser et al., 2004), the use of blue traps could be advisable if *M. pygmaeus* is used to control other pest species. For instance, *F. occidentalis* is mainly attracted to blue colour (Gillespie and Vernon, 1990; Montserrat et al., 2000; Natwick et al., 2007) and consequently blue traps are already used for its monitoring in cucumber and other crop. Although it remains to be tested for each crop under practice conditions, our results indicate that blue traps may as well be suitable to monitor *M. pygmaeus* and *F. occidentalis* together.

## Monitoring of *T. vaporariorum*

Monitoring of *T. vaporariorum* using yellow sticky traps is a standard technique in protected tomato and several other crops. In the current study, *T. vaporariorum* was found on yellow traps at all locations before its first detection in the crop. This finding supports the common use of yellow traps in commercial greenhouses for early detection and the known preference of *T. vaporariorum* for yellow as compared to green colour (Webb et al., 1985; Johansen et al., 2011).

There were no structural differences in scatterplots for the relation of plant and trap counts between the 3 commercial greenhouses (Figure 5B), and consequently data of all commercial greenhouses was combined for modelling. Similar as in a previous study under standardised experimental conditions (Böckmann et al., 2014), correlations between adult trap catch and adult or nymph density on the crop were highly significant. The current results also confirm the prior finding that correlations of nymphal counts with trap catches are more accurate as compared to adult counts (Figure 5B). The reasons for increased accuracy of correlation between adult trap catch and nymphal as compared to adult counts in the crop are discussed in detail in Böckmann et al. (2015) (Chapter 1).

Our current and the previous study encourage the use of adult trap catches at practice relevant densities to predict nymphal densities in the crop, a strategy also proposed in the review by Pinto-Zevallos and Vänninen (2013). Based on the current study, this advice can be confirmed for poly-tunnel of up to 300 m² and glasshouses of up to about 800 m².

In the commercial glasshouse, control was considered to be insufficient in mid of July and consequently, additional introductions of *E. formosa* were carried out (Figure 2). However, no extensive contamination with honeydew was observed and whitefly larvae per leaf at July 17$^{nth}$ were on average 0.5 ± 0.4 (mean ± SD). The mentioned growers' decision rules underline, that no practice relevant threshold for this pest in tomato crop exists. The only threshold for that crop we are aware of was described by Hussey et al. (1958), showing that at infestations as heavy as 70 nymphs per 5 cm² about 30 % of fruits show some sooty mould and at 130 nymphs yield is reduced. Our example shows that, in practice, growers apply their personal threshold and frequently accept only much lower pest densities on their crop.

Although repeatedly introduced in all greenhouses, *E. formosa* was unable to establish a population when it was released in addition to *M. pygmaeus*. Rarely pupae of the parasitoid (i.e. black whitefly nymph) on the crop or adult parasitoids on a yellow trap were observed. However, because the parasitoid was introduced repeatedly and in much higher densities as compared to *M. pygmaeus*, it most likely had a considerable impact on pest population build up due to host feeding on whitefly larvae. The latter is also indicated when comparing the population build-up of *T. vaporariorum* in the commercial glasshouse and both commercial poly-tunnel during May and June (Figure 3). Population build up was steeper at that time span in the commercial glasshouse, the only site where no *E. formosa* was introduced at that time. However, this impact cannot be distinguished visually from predation by *M. pygmaeus* and abiotic factors causing death on whitefly larvae.

# Conclusion

Our results show that accurate sticky trap monitoring does not necessarily rely on strong colour attraction of the target insect. That is at least true under conditions, where early detection is not crucial and relatively high numbers of the target insects are expected to occur and are of major interest, i.e. for released natural enemies in protected crops. In the concrete case, monitoring of *M. pygmaeus* can be done with yellow or blue traps, because the adult predatory bug responds indifferently to both colours. For other crops than tomato these assumptions remain to be tested. It is however likely that monitoring of this important natural enemy can be integrated into existing monitoring-strategies by sticky traps, no matter if blue or yellow traps are in use. The fortune is that by using the traps already present for pest monitoring, there are no additional material costs and little increase of workload. Correlations established for *M. pygmaeus* (current study), *E. formosa* (Böckmann et al., 2015; Chapter 1) and *T. vaporariorum* (current study) were validated in commercial greenhouses in 2014 (Chapter 3).

# Chapter 3

# Steps towards automated decision making in integrated pest management using practice relevant monitoring schemes

## Abstract

Integrated Pest Management (IPM) becomes more and more standard in agricultural production. With it, also complexity of decision making for optimal pest control keeps increasing, due to the application of thresholds for economic pest damage and establishment of biological control, and the need to choose for selective insecticides. The key for optimal decision making is a reliable (but also cost and labour efficient) monitoring, at its best enabling growers to area-specific adaption of control measures. When targeting alate insects, sticky traps have good potential to provide such monitoring, as long as correlations of trap catch with on-crop densities can be established and enables accurate predictions in new growing seasons. In the current study we validate yellow trap monitoring of the Greenhouse Whitefly, *Trialeurodes vaporariorum*, and its natural enemies *Encarcia formosa* and *Macrolophus pygmaeus*. Therefore we apply the correlations established in previous studies on data of a new tomato season, and evaluate the accuracy with regard to certain threshold levels. Accuracy of prediction based on trap catch for damaging levels in complete greenhouses (greenhouse areas) was 89 % (84 %) for *T. vaporariorum* nymphs. For adults, validation failed because the prediction did never exceed the tentative damaging level. Established biological control by the parasitoid, i.e. parasitism rates <80 %, was predicted by adult trap catch with 92 % (96 %) accuracy. A level of 5 *M. pygmaeus* nymphs and adults per plant was assumed as established control, and predicted with 86 % (88 %) accuracy. Population peaks were strongly underestimated for both whitefly stages, and parasitism rates of *E. formosa* were only accurately predicted for rates above 50 %, whereas population development of *M. pygmaeus* was accurately predicted throughout season. Furthermore, we could show that a monitoring driven introduction of *E. formosa* can pay of economically in means of material costs, as compared to introduction of one or both beneficials in predefined intervals. Implications of these results for IPM programs on *T. vaporariorum* are discussed.

**Key words:** Decision Support System, Economic Injury Level, *Plant Protection*, Beneficials

# Introduction

Crop protection strategies have undergone remarkable changes within the last decades. Driven by the resistance of important pest species due to repeated application of broad range pesticides, to date plant protection often relies on a combination of beneficials and more specific plant protection products (van Lenteren 2000). This process is to date reinforced by increasingly restricted registration procedures for plant protection products by the countries, reseller demands and consumer preferences. As a result, the number of growers applying the rules of integrated pest management (IPM) in plant protection is constantly increasing. In IPM, pest control relies primarily on naturally occurring, modified or introduced biological control (Stern et al. 1959). Pesticides should only be applied if pest populations reach damage inflicting densities. Also negative impact of pesticides on beneficials should be minimized, especially in crops where beneficials are introduced and sustained on the crop. To date introduction of beneficials is standard in most protected vegetables in Europe, but also in different areas around the world and even in some broad acre crops (van Lenteren 2000; van Lenteren 2007; Gardner et al. 2012). The combination of chemical and biological control together with a rapid change of registered products, has increased complexity in plant protection and resulted in a need of growers for decision support. For decision making in pest control, the information needed are 1) which beneficials should be introduced in which density and frequency (i.e. how can the pest be effectively and cost saving controlled), 2) was beneficial quality and were environmental conditions adequate for introduction (i.e. does beneficial population build up as expected), 3) when does the control become effective (i.e. when can introductions be finished) and 4) did the pest (or in some cases the beneficial) population reach a predefined damaging threshold (i.e. is there a need to adapt control measures). Most information on beneficial introductions is provided by the producing companies. These companies presumably follow several goals with the provided information. First of all they should assure that effective pest control is reached in the crop. However, they should also have an interest in selling their products, preferably at predefined timetables and amounts. Hence, if no independent evaluation takes place, the use of beneficials potentially becomes extended from early to late season, irrespective of pest occurrence and established control. This extension is neither necessarily in line with growers' costs of goods perspective nor with the IPM concept.

To truly apply the IPM strategy, all decisions that are taken in plant protection have to rely on a comprehensive monitoring, including the target pests and its natural enemies and should be related to predefined thresholds. Mainly two thresholds, both described by Stern et al. (1959), are applied to define that pest density. One is the economic injury level (EIL) which gives the density at which a control measure that is taken equals in costs the damage a given pest density inflicts. The second one is the economic threshold (ET), which defines the pest density at which a control measurement should be initiated in order to prevent pest densities from reaching the EIL. Both thresholds vary from area to area, season to season or with man's changing scale of economic values (Stern et al. 1959; Damos 2014). Thresholds from literature may therefore only be taken for orientation purposes, but have to be adapted individually to every location. For several important pest species, thresholds can be found in recent literature (Brewer et al. 2013; Andreev et al. 2013; Shirvani-Farsani et al. 2013; Mujica and Kroschel 2013; Paula-Moraes et al. 2013; Bueno et al. 2013). Also for some beneficials there exist practice recommendations for population densities or density relations (pest – beneficial) indicating that control of the pest is established (Fischer and Terrettaz 2003; Albert et al. 2007; Brun et al. 2012; Scholz-Döblin 2013; Böckmann et al. 2014). If beneficials also feed on plant material and therefore may damage the crop when occurring in high densities, growers need to decide on their control as well. The latter is for instance the case for many mirid predators, such as *Macrolophus pygmaeus*, *Dicyphus tamaninii*, *Dicyphus Hesperus* and *Nesidiocoris tenuis* (Castañé et al. 2011).

In order to reduce monitoring workload for growers, indirect measures of pests using sticky traps became established in many cropping systems (Ohnesorge and Rapp 1986; Pinto-Zevallos and Vänninen 2013). It is however essential to relate trap catch to pest and beneficial densities on the crop. For trap monitoring, several publications show correlations between trap catch and actual pest densities, but many of these studies considered monitoring density and / or frequency too laborious for practice (Hoffmann et al. 1997; Shipp et al. 2000; Karut and Kazak 2007; Natwick et al. 2007; Pizzol et al. 2010). As a result, growers and pest control advisors broaden monitoring schemes without further validation in order to make them applicable

(Cullen et al. 2000). There are also examples of studies which consider practice relevant monitoring schemes (Higgins 1992; Kim et al. 2001; Macintyre-Allen et al. 2005; Pascual-Ruiz et al. 2014). However, with view on application all the latter studies lack the validation of the described correlations (pest trap catch – pest densities on plants) with independent data sets, i.e. on data sets collected at another study site or year, which was not used to establish the correlation. Another lack in literature is the development of structured monitoring of beneficials (but: Karut and Kazak 2007). However, one recent study on the soybean aphid covered all mentioned fields (practice relevant monitoring, pest and beneficial monitoring, validation in practice), and described a complete, applicable decision support system (DSS) for growers of the broad acre crop soybean (Hallett et al. 2014).

During the last 3 years we developed enhanced monitoring schemes for protected tomato crop that are conclusive and at the same time applicable for growers (Böckmann et al. 2014). Furthermore we implemented the established correlations and dependent decision rules in a DSS (Böckmann and Meyhöfer 2015). Thereby we considered the information content of trap catch on pest densities of *Trialeurodes vaporariorum* and its most important natural enemies, namely *Encarsia formosa* and *Macrolophus pygmaeus*, on the crop. For the pest there is no practice relevant threshold available from literature. Hussey et al. (1958) found that a reduction in tomato yield occurs at 70 nymphs / 5 cm² leaf area. However, in practice the whitefly density accepted by growers is much lower due to nuisance by flying adults and distribution of honey dew on plants (personal communication). Tomato growers in the Netherlands and Germany assume 3-7 *M. pygmaeus* per plant as a level of established control (Joke de Jong, Markus Knapp, Theo Reintges personal communication), whilst a level of more than 10 individuals per plant is considered as potentially damaging (Joke de Jong, personal communication). However, in literature damage of tomato crop is considered to mainly occur at very high predator densities and low prey availability under experimental conditions (Castañé et al. 2011). For *E. formosa* a parasitism rate of at least 80 % is considered as established control (Scholz-Döblin 2013). Because nowadays greenhouses of more than 1 ha in size are not out of the ordinary, and due to the aggregated occurrence of many pests (Taylor 1984; Noldus et al. 1986), area specific recommendations within one greenhouse are needed to optimize decision making in pest control. In this study we validate the accuracy of yellow trap catches as an estimate of population density on individual crop areas within greenhouses (monitored by a single yellow trap) as compared to the complete greenhouse area, based on the monitoring schemes recommended in our previous studies for the pest and both beneficials (Böckmann et al. 2015, Chapter1, Chapter 2). Furthermore, we estimate if decisions based on trap catch related to the mentioned thresholds are as accurate when taken based on trap catches, as decisions based on direct counts on plants. The differences in costs of goods of applying those decision rules as compared to standard introduction intervals are discussed.

# Material and Methods

In all tomato greenhouses, a regular grid of yellow sticky traps was installed, with traps hung on top plant level. Trap position was adjusted to plant level until crop reached maximum height. Pests and beneficials on the tomato crop were counted at 3 levels per plant (top, intermediate and bottom) at 3 full leaves per plant level (i.e. 9 leaves per plant). Numbers of target pests and beneficials were counted weekly (2012) or fortnightly (2013/14) on traps and plants. Details on numbers of yellow traps, rating plants, target pests and released beneficials are summarized for all sites in table 1. Introduction intervals and densities of beneficials, tomato growth and rating period as well as abbreviations used for the different sites are summarized in table 2.

**Table 1** Summary of greenhouse sizes, trap densities and rating schemes of pest (TV = *T. vaporariorum*) and beneficials (EF = *E. formosa*; MP = *M. pygmaeus*), of all monitored greenhouses and poly-tunnel (greenhouse = GH, greenhouse chamber = GH-C, experimental greenhouse = GH-Exp, poly-tunnel = P-T).

| Site | Year | Size ($m^2$) | Traps (ha) | Rating plants per trap | Rating interval (d) | Insects monitored |
|---|---|---|---|---|---|---|
| **GH-C** | 2012 | 40 | 500 | 4 | 7 | / |
| **GH-Exp** | 2012 | 170 | 588 | 3 | 7 | TV, EF |
| **P-T-1** | 2013 | 300 | 100 | 2 | 14 | TV, EF, MP |
| **P-T-2** | 2013 | 300 | 100 | 2 | 14 | TV, EF, MP |
| **GH-1** | 2013 | 780 | 77 | 2 | 14 | TV, EF, MP |
| **GH-2** | 2013 | 700 | 86 | 2 | 14 | TV, EF |
| **GH-3** | 2013 | 350 | 86 | 2 | 14 | TV, EF |
| **P-T-1** | 2014 | 300 | 67 | 4 | 14 | TV, EF, MP |
| **P-T-2** | 2014 | 300 | 67 | 4 | 14 | TV, MP |
| **GH-1** | 2014 | 780 | 51 | 4 | 14 | TV, EF |
| **GH-2** | 2014 | 700 | 57 | 4 | 14 | TV, EF |
| **GH-3** | 2014 | 350 | 57 | 4 | 14 | TV, EF |
| **P-T-3** | 2014 | 270 | 74 | 4 | 14 | TV, EF |

## *Data collection 2012*

Experiments considered in the current study were carried out in one experimental greenhouse (GH-Exp) and one experimental greenhouse chamber (GH-C). In both locations, crop was infested artificially with *T. vaporariorum* adults and control was established by introductions of *E. formosa* (Table 2). For details on cropping systems and experimental setup, please consider the original study from Böckmann et al. (2014).

## *Data collection 2013*

Experiments considered in the current study were carried out in five commercial greenhouses. In all locations, natural occurrence of *T. vaporariorum* was awaited and growers decided on introduction of beneficials (Table 2). For details on cropping systems and experimental setup of the commercial greenhouse (GH-1) and both commercial poly-tunnel (P-T-1, P-T-2), please consider the original study (Chapter 2). Two commercial greenhouses were not considered in the previous study, because neither *T. vaporariorum* nor *E. formosa* became established in these greenhouses (GH-2, GH-3). These houses will be considered in the current study for the economic evaluation of different introduction schemes of beneficials. In GH-2, 1170 beef tomato plants (different cultivars) were grown to a maximum plant height of 3.5 m. In GH-3, 590 cocktail tomato plants (different cultivars) were grown to a maximum plant height of 2.5 m. In both greenhouses, plants were arranged in 5 double rows and plants were gradually shifted sideways using tomato hooks (for details see Table 1 and 2).

**Table 2** Growing period in calendar weeks (CW, grey shaded) of all greenhouses (greenhouse = GH, greenhouse chamber = GH-C, experimental = Exp, poly-tunnel = P-T) and years. Growing period is consistent with rating period for all but P-T-3, where rating started at calendar week 30. First pest occurrence is indicated by TV (*T. vaporariorum*), introductions of beneficials by MP (*M. pygmaeus*) and EF (*E. formosa*). Numbers refer to individuals introduced per m².

| Year | 2012 | 2012 | 2013 | 2013 | 2013 | 2013 | 2013 | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GH / CW | GH-C | GH-Exp | GH-1 | GH-2 | GH-3 | P-T-1 | P-T-2 | GH-1 | GH-2 | GH-3 | P-T-1 | P-T-2 | P-T-3 |
| 10 | | | ▨ | ▨ | ▨ | | | | ▨ | ▨ | | | |
| 11 | | | 0.5 MP | ▨ | ▨ | | | | ▨ | ▨ | | | |
| 12 | | | ▨ | ▨ | ▨ | | | | ▨ | ▨ | | | |
| 13 | | | ▨ | ▨ | ▨ | ▨ | ▨ | | ▨ | ▨ | | | |
| 14 | | | 0.5 MP | ▨ | ▨ | 1 MP | 1 MP | | ▨ | ▨ | | | |
| 15 | | | ▨ | ▨ | ▨ | TV | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | |
| 16 | | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 0.5 MP | 0.5 MP | ▨ |
| 17 | ▨ | ▨ | TV | ▨ | ▨ | 1 MP | TV<br>1 MP | ▨ | ▨ | ▨ | TV | TV | ▨ |
| 18 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 19 | ▨ | ▨ | ▨ | ▨ | ▨ | 5 EF | 5 EF | ▨ | ▨ | ▨ | 0.5 MP<br>1.5 EF | 0.5 MP | ▨ |
| 20 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 21 | TV | TV | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 1.5 EF | ▨ | ▨ |
| 22 | 5 EF | 5 EF | ▨ | ▨ | ▨ | 5 EF | 5 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 23 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 1.5 EF | ▨ | ▨ |
| 24 | 5 EF | 5 EF | ▨ | ▨ | ▨ | 5 EF | 5 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 25 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 26 | 5 EF | 5 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 27 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 28 | 5 EF | 5 EF | 6.4 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 3 EF | TV<br>3 EF |
| 29 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | TV | ▨ | TV | ▨ | ▨ | ▨ |
| 30 | 5 EF | 5 EF | 6.4 EF | ▨ | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | 3 EF | 3 EF |
| 31 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | TV | 3 EF | ▨ | ▨ | ▨ |
| 32 | 5 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | 3 EF | 3 EF |
| 33 | ▨ | ▨ | 6.4 EF | TV | TV | ▨ | ▨ | ▨ | 3 EF | 3 EF | ▨ | ▨ | ▨ |
| 34 | 5 EF | ▨ | ▨ | 5 EF | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | ▨ | 3 EF |
| 35 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | ▨ |
| 36 | 5 EF | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | ▨ | 3 EF |
| 37 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 3 EF | ▨ | ▨ | ▨ | ▨ |
| 38 | ▨ | ▨ | ▨ | ▨ | | ▨ | ▨ | 3 EF | ▨ | | ▨ | ▨ | ▨ |
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## Data collection 2014

Experiments were carried out in all commercial greenhouses monitored in 2013 (Table 1). Cropping system in greenhouses already monitored in 2013 remained the same as described above and in Chapter 2. Data collection was carried out likewise as described for the previous years. Numbers of yellow traps per greenhouse were slightly reduced to be able to increase number of monitored plants with manageable workload (Table 1). One additional unheated commercial poly-tunnel, with different cultivars of cocktail tomato was monitored in 2014 (P-T-3). In this tunnel, tomato plants were arranged in 40 single rows of 10 plants each at right angle to tunnel length. Plants were grown to a maximum height of 2.0 m and growing tips where cut thereafter, at August 11. Monitoring started in calendar week 30, whereas planting was in calendar week 16. Because *T. vaporariorum* was immediately detected when installing the yellow sticky traps in calendar week 28, it is likely that the pest was present already earlier in the season. Additionally to the assessments already taken in previous years, number of leaves per plant was counted on 5 randomly selected plants at every sample date and location. This count was used as a factor to convert from insect counts on 9 leaves to the practice relevant plant unit. Temperature was measured in 10 min intervals throughout experiments and average temperatures including all measures (°C, mean ± SD) were 20.18 ± 5.16 in GH-1, 20.65 ± 4.99 in GH-2, 21.51 ± 4.78 in GH-3, 21.13 ± 6.12 in P-T-1, 20.36 ± 5.79 in P-T-2 and 19.96 ± 6.01 in P-T-3.

## Statistical analyses

### *Training of models*

Based on the data collected in 2012 / 13, numbers of pests and beneficials trapped were correlated with their numbers on the crop, by fitting of linear models. Therefore averages were calculated for insects counted per plant (i.e. on 9 leaves) as well as for insects caught per sticky trap, for each monitoring date, including all rated plants or traps. Data were ln (x + 1) transformed prior to analysis. The use of untransformed data (i.e. sums instead of averages) was not possible in these cases, because the number of traps per greenhouse as well as the relation of rating plants as compared to yellow traps changed between locations and within years.

For *E. formosa*, two datasets from 2012, both published in Böckmann et al. (2014), were used (GH-Exp, GH-C). Modelling procedure remained the same, but data from the greenhouse and the greenhouse chamber were combined to fit the current models. On the one hand, a linear model was fitted, using the procedure described above. To account for the problem that parasitism rate increased unrealistically (above 100 %), additionally a binominal generalized linear model with logit-link was fitted, using the average trap catch as an independent and the proportion of unparasitized to parasitized nymphs as dependent variable.

For *M. pygmaeus* and *T. vaporariorum*, models were trained using the data from three commercial greenhouses monitored 2013, in which the respective pest and beneficial became established and reached meaningful densities (GH-1, P-T-1, P-T-2). The datasets and the linear models applied in the current study were described in Chapter 2. Datasets from the experimental sites monitored in 2012 were not included for *T. vaporariorum*, because cropping system and density of traps differed largely from the commercial sites monitored in 2013/14.

### *Application of models*

In the current study, the established models are applied on the new datasets collected in 2014, giving 1) a prediction of population density on crop for every greenhouse area monitored by a single trap and 2) a prediction of population density on crop for each entire greenhouse. All predictions refer to the mean number of insects or developmental stages of insects counted on 9 leaves per plant and are based on the trap catch of the respective adult stage. In order to translate average counts of population densities on 9 leaves per plant to the practice relevant plant unit, the average leave count at the respective greenhouse and date was used as factor, to calculate the average number of insects per plant (i.e. average count per 9 leaves / 9 * average leaf number per plant). The predicted values of the models were transformed accordingly. For every model applied, a 95 % confidence interval is given and the accuracy of model predictions on important thresholds was evaluated. Although a prediction interval would have been favourable in case of linear model predictions, the latter cannot be calculated for generalized linear models. Hence, for reasons of uniformity, the confidence interval was used at all times. Thresholds tested included:

Established control *E. formosa*:

A parasitism rate of *E. formosa* ≥ 80 %

Established control *M. pygmaeus*:

A density of *M. pygmaeus* (nymphs and adults) > 5 individuals per tomato plant

Damaging level *M. pygmaeus*:

A density of *M. pygmaeus* (nymphs + adults) > 10 individuals per tomato plant

Damaging level *T. vaporariorum* nymphs (tentative damaging level):

A density of *T. vaporariorum* nymphs above 10 nymphs per plant

Damaging level *T. vaporariorum* adults (tentative damaging level):

A density of *T. vaporariorum* adults above 5 adults per plant

The analysis was carried out by calculation of the proportion of true and false predictions. Requirements for a true prediction were given, if a model showed correctly that control was established or that a damaging level was reached (true positive), or that the respective level was not reached (true negative). Requirements for a false prediction are given if a model predicts incorrectly one of the mentioned scenarios (actual population below threshold, prediction above threshold = false positive; actual population above threshold, prediction below threshold = false negative). For prediction of beneficial establishment, an error of 10 % was allowed for false negative predictions; for damaging thresholds, an error of 10 % was allowed for false positive predictions. An error of 5 %, was allowed for false positive prediction of beneficial establishment and for false negative prediction of reaching of damaging thresholds, by pest or beneficial. Thresholds are evaluated using a Likelihood-Ratio-Test, including data from all dates of all greenhouses monitored in 2014, in which the corresponding pest or beneficial was present. Predictions for greenhouse areas and complete greenhouses were calculated separately.

## Economical analyses

In this article it will be analysed if the decision rules implemented in the decision support software AEP (Automatische Entscheidungshilfe für den Pflanzenschutz unter Glas) (Böckmann and Meyhöfer 2015, Chapter 4) pay off economically. The software recommends the use of *E. formosa* alone for greenhouse tomato with a growing period <9 month, and to start introductions when the first *T. vaporariorum* is detected. Only recently, distributers of beneficials tend to recommend *M. pygmaeus* also for tomato summer cultures (personal communication with growers). Recommendations range between 0.5 and 1 *M. pygmaeus* / m² with 2 introductions. Sometimes, additional introductions of *E. formosa* are recommended, with 1.5 *E. formosa* / m² and 3 introductions, in order to guarantee pest control in the early season. Distributers advise to provide lepidopteran eggs as an additional food source for *M. pygmaeus*, if pest is absent or present in low densities (*Ephestia kuehniella* eggs: Koppert B.V. (ENTOFOOD) and Biobest Belgium NV (Nutrimac™); *Sitrotoga* sp. eggs: Katz Biotech GmbH, Germany). Previously to the commercialisation of *M. pygmaeus*, the introduction of *E. formosa* alone was recommended. Although the official recommendation of most suppliers is to use this beneficial curatively and until control is established, applications are commonly realised in standard intervals, using 3-5 *E. formosa* / m² every second week throughout growing season (personal communication with several suppliers and growers).

Based on these recommendations, the following introduction schemes are evaluated economically for the greenhouses monitored in 2014 (P-T-3 was excluded from these analyses, because monitoring started too late to assure detection of first pest occurrence in the crop):

<u>MP standard:</u> *M. pygmaeus* only, with 2 introductions of 0.5 individuals / m² plus *Sitrotoga* sp. eggs.

<u>MP safe:</u> *M. pygmaeus*, with 2 introductions of 0.5 individuals / m² plus *Sitrotoga* sp. eggs and 3 introductions of *E. formosa* with 1.5 individuals / m².

<u>EF standard:</u> *E. formosa* only, with introdutions every second week throughout growing season, until 4 weeks before end of season) with 3 individuals / m².

<u>EF adapt:</u> *E. formosa* only with 3 individuals / m², begin 1 week after first pest detection until 4 weeks before end of season or established control, i.e. 80 % parasitism rate.

The evaluations include costs of beneficials, artificial food and yellow traps. Yellow trap (10*25 cm) costs were only included in the EF adapt scheme, in which introductions were triggered by monitoring results. Trap numbers used are indicated in Table 1, and monthly exchange of traps was assumed. Costs were calculated based on the single package price, indicated for commercial growers in 2014 by Katz Biotech GmbH (Baruth, Germany), and were extrapolated for each greenhouse area. Costs of work load for monitoring, introduction of beneficials or yellow traps and delivery of products, were not considered.

# Results

## Prediction accuracy of *Trialeurodes vaporariorum* density on crop

Linear models were trained for prediction of two development stages of the pest, namely the adult stage and the larval stage (Table 3). Densities of both stages differed largely between greenhouses in 2014. For both stages, highest densities were reached in P-T-1 and P-T-2 with maximum pest densities in the complete greenhouse of on average 30 or 120 nymphs/plant and 15 or 9 adults / plant. These were also the greenhouses where the pest became established directly at begin of the season in 2014, and hence 12-13 weeks before establishment in the other houses took place (Table 2). Predictions of the nymph numbers followed the population trends in these greenhouses, but heavily underestimated the population peaks in P-T-2 (Figure 1). For P-T-3 and GH-1 the population densities where well predicted, but population densities remained constantly low in these greenhouses (Figure 1). The population peak in greenhouse area 4 of GH-1 was approximately 5-fold underestimated. This effect was partly compensated if the complete greenhouse was considered.

Adult numbers per plant were 5-10 fold lower than nymph numbers (Figure 2). A good prediction of adult densities could be achieved for the greenhouses P-T-1, P-T-3 and GH-1. However, none of these populations showed pronounced peaks over the growing season. The population peak in the P-T-2 could not be predicted and was underestimated by approximately 5-fold (Figure 2).

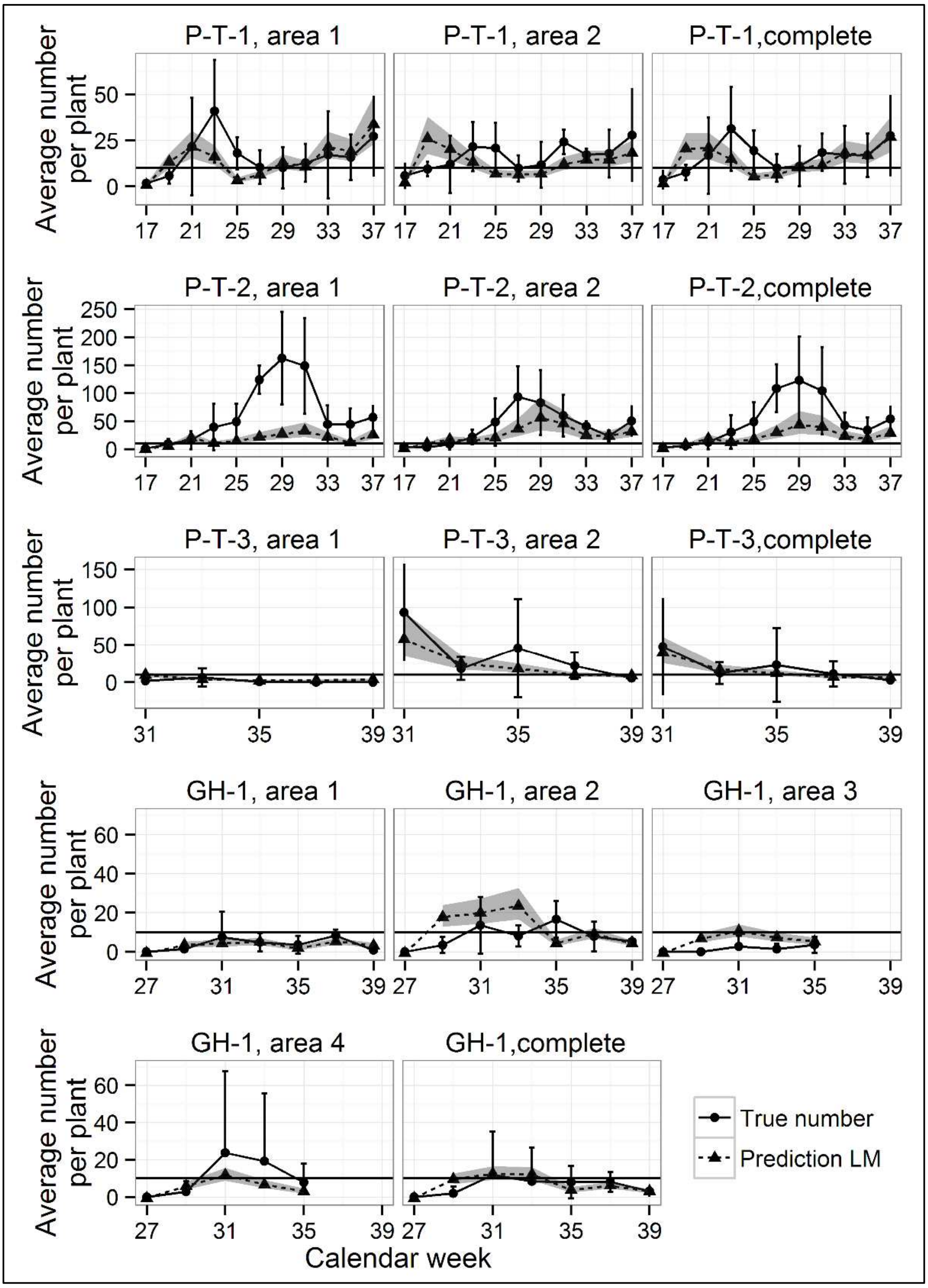

**Figure 1** Average number of *T. vaporarionrum* nymphs per plant in the Commercial Poly-Tunnel-1 (P-T-1), 2 (P-T-2), 3 (P-T-3) and the Commercial Greenhouse-1 (GH-1), calculated based on counts (True number), and predicted by the linear model based on adult trap catch (Prediction LM). A 95 % confidence interval is given (grey shade). A tentative damaging level at > 10 nymphs / plant is included (black horizontal line). All estimates are given for each greenhouse area monitored by a single yellow trap, and for each complete greenhouse based on the averaged count of all traps (GH-1: N = 4; P-T-1, 2 and 3: N = 2). Nymph counts per plant (i.e. on 9 leaves) were averaged based on all plants in the respective greenhouse area (4 plants per area) or the complete greenhouse (GH-1: N = 16; P-T-1, 2 and 3: N = 8).

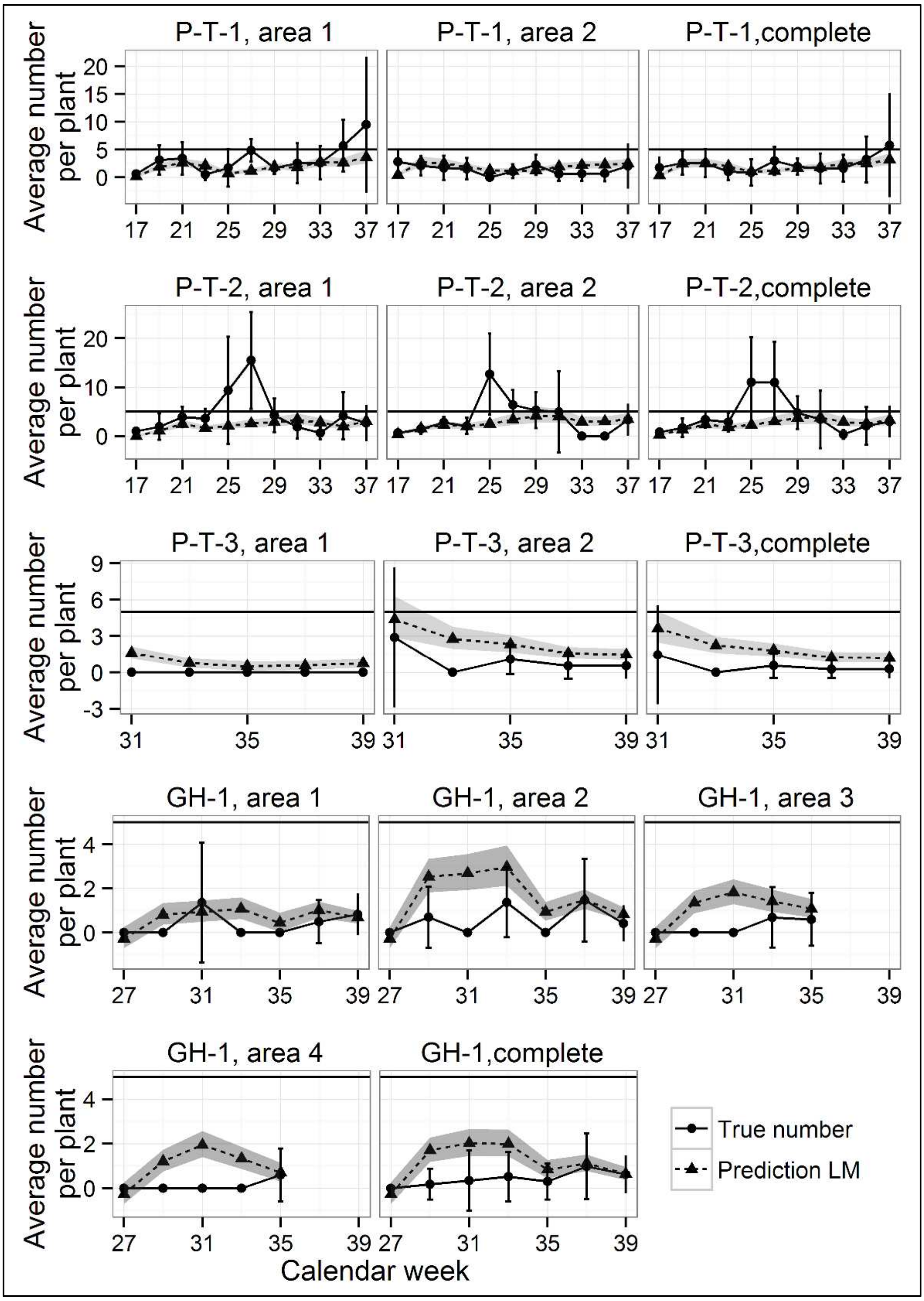

**Figure 2** Average number of *T. vaporariorum* adults per plant in the Commercial Greenhouse-1 and the Commercial Poly-Tunnel-1, 2 and 3, calculated based on counts (True number), and predicted by the linear model based on adult trap catch (Prediction LM). A 95 % confidence interval is given (grey shade). A tentative damaging level at >5 adults / plant is included (black horizontal line). All estimates are given for each greenhouse area monitored by a single yellow trap, and for each complete greenhouse based on the averaged count of all traps (GH-1: N = 4; P-T-1, 2 and 3: N = 2). Adult counts per plant (i.e. on 9 leaves) were averaged based on all plants in the respective greenhouse area (4 plants per area) or the complete greenhouse (GH-1: N = 16; P-T-1, 2 and 3: N = 8).

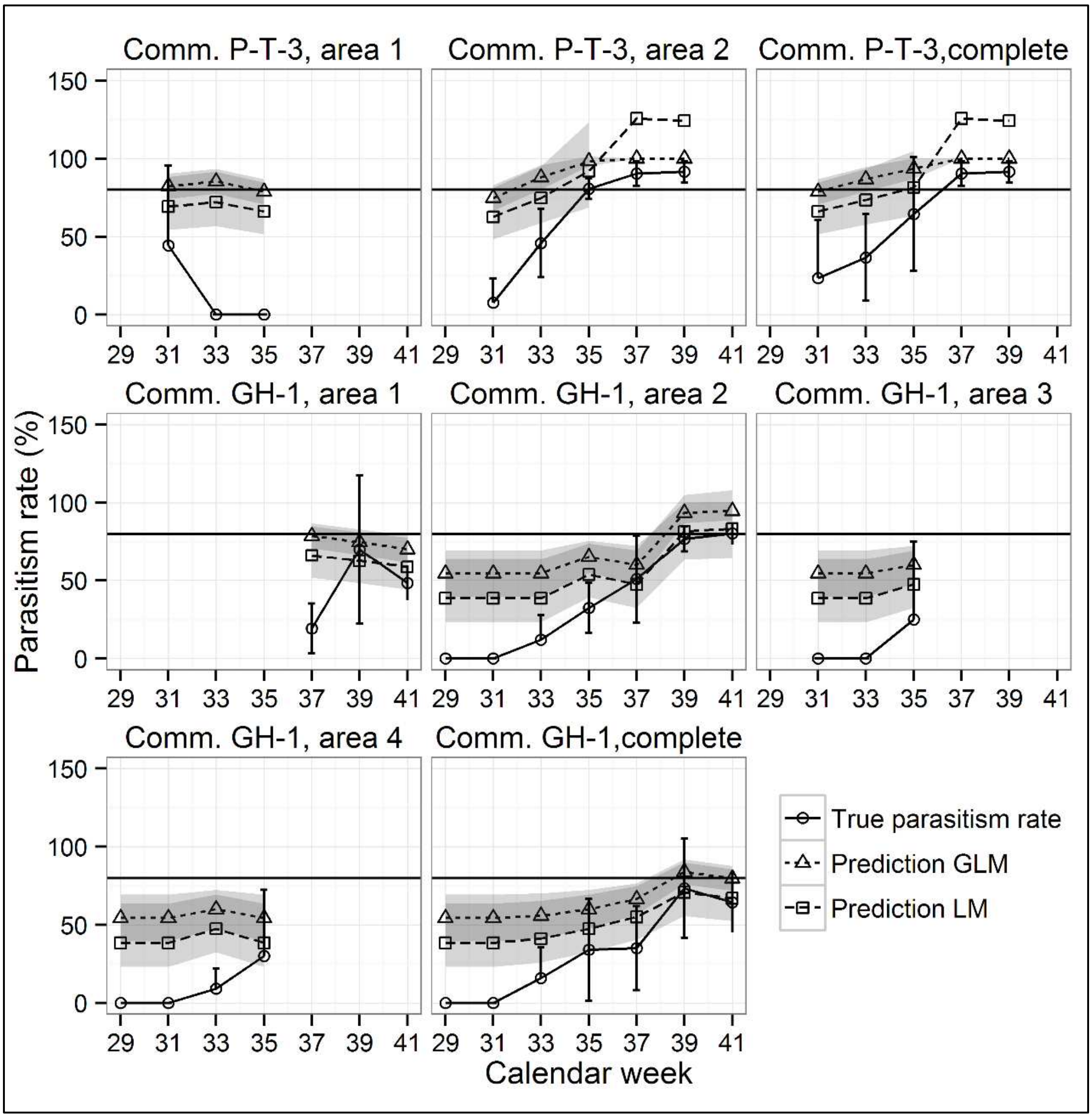

**Figure 3** Average parasitism rate of *E. formosa* in the Commercial Poly-Tunnel-3 and the Commercial Greenhouse-1 calculated based on counts, and predicted by either a linear model (Prediction LM) or a generalized linear model (Prediction GLM) based on parasitoid trap catch. A 95 % confidence interval is given for each model (grey shade). Control of *T. vaporariorum* is assumed to be established at 80 % parasitism (black horizontal line). All estimates are given for each greenhouse area monitored by a single yellow trap and for each complete greenhouse based on the averaged count of all traps (P-T-3: N = 2; GH-1: N = 4). Parasitism rate was first calculated per plant (i.e. based on the count of parasitized and intact nymphs of *T. vaporariorum* on 9 leaves) and then the average was calculated based on all plants in the respective greenhouse area (4 plants per area) or the complete greenhouse (P-T-3: N = 8; GH-1: N = 16). Plot area was chosen for optimal visualization of the data rather than to include the full confidence interval (grey shade) or negative error bars at all times.

Taking the strong underestimation of the population peak into account, prediction of the tentative damaging threshold for nymphs (> 10 nymphs / plant) was rather accurately predicted for the greenhouse areas, and even better for the complete greenhouses (Table 4). In case of adults, the tentative damaging level (> 5 adults / plant) was accurately predicted at no time. However, that level was reached only 7 times in a greenhouse area and 3 times in a complete greenhouse (Table 4, Figure 2).

## Prediction accuracy of *Encarsia formosa* parasitism rate

Two models, one LM and one GLM, were fitted and applied for prediction of parasitism rate in both greenhouses (Table 3). Low parasitism rates were strongly overestimated by both models, because the LM predicts already a level of 38 % parasitism and the GLM even 54 % parasitism, without any trap catch of the parasitoid (Figure 3). Although the intercept in case of the GLM was not significant, omitting the intercept did not enhance model fit (data not shown). However, prediction of parasitism rates from 50 and 80 % were accurately predicted by the LM, whereas the GLM overestimated these rates.

In P-T-3, monitoring started late and therefore the first occurrence of the pest remains unclear. In GH-1, parasitoid introduction started late in the season, in accordance with the detection of *T. vaporariorum* (Table 2). After introduction of *E. formosa*, a steep increase of parasitism rate was found in both greenhouses (Figure 3).

**Table 3** Models for prediction of on-crop population based on trap catch, trained on the datasets available from 2012 (*Encarsia formosa* = *EF*) and 2013 (*Macrolophus pygmaeus* = *MP*, *Trialeurodes vaporariorum* = *TV*). In case of linear models, average counts or rates were ln (x + 1) transformed prior to analyses. The generalized linear model was carried out with a binomial assumption (logit-transformation) of parasitism rates calculated using the sums of parasitized and intact nymphs of *T. vaporariorum*.

| Insect | Model | Response | Factor | Estimate ± SE | p | $df_{num}$<br>$df_{den}$ | F | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| ***MP*** | LM | Aduls + nymphs | Intercept | -0.128 ± 0.114 | 0.271 | 1 | 33.3 | 0.47 |
| | | | Slope | 0.185 ± 0.321 | **<0.001** | 37 | | |
| ***TV*** | LM | Nymhs | Intercept | -0.355 ± 0.215 | 0.107 | 1 | 87.2 | 0.70 |
| | | | Slope | 0.562 ± 0.060 | **<0.001** | 37 | | |
| ***TV*** | LM | Adults | Intercept | 0.177 ± 0.135 | 0.199 | 1 | 113.0 | 0.75 |
| | | | Slope | 0.687 ± 0.065 | **<0.001** | 37 | | |
| ***EF*** | LM | Parasitism rate | Intercept | 3.676 ± 0.213 | **<0.001** | 1 | 10.9 | 0.58 |
| | | | Slope | 0.297 ± 0.090 | **0.011** | 8 | | |
| ***EF*** | GLM | Parasitism rate | Intercept | 0.176 ± 0.306 | 0.575 | 20 | 16.0 | / |
| | | | Slope | 0.227 ± 0.066 | **0.003** | 21 | | |

The threshold level of 80 % parasitism was reached only in the greenhouse area 2 and the complete greenhouse in case of P-T-3 and in the greenhouse area 2 in GH-1. In the latter greenhouse area, the establishment was predicted two weeks before the threshold level was reached, at an actual parasitism rate of 77 %, which is tolerable. At the next monitoring date both, the prediction and the actual parasitism rate reached 80 %. In P-T-3, plant quality changed rapidly in greenhouse area 1 and therefore, monitoring on plants was not possible in this area after calendar week 35. However, it seems likely that parasitoids emigrated from that area and were trapped in greenhouse area 2, resulting in an overestimation of parasitism rate in that area and the complete greenhouse (Figure 3). Prediction of ≥ 80 % parasitism rate was two weeks early for the complete greenhouse, but was in time for greenhouse area 2.

**Table 4** Accuracy of threshold prediction by trained models (linear model = LM, generalized linear model = GLM), based on yellow trap catch, for population densities on crop indicating establishment of beneficials (*EF* = *Encarsia formosa*, *MP* = *Macrolophus pygmaeus*) and damaging by pests (*TV* = *Trialeurodes vaporariorum*). For the beneficial *M. pygmaeus*, also a damaging threshold of >10 insects/plant is evaluated. Criteria evaluated were true (predicted and observed above threshold = true positive; predicted and observed below threshold = true negative) and false predictions (predicted below and observed above threshold = false negative; predicted above and observed below threshold = false positive). For damage thresholds (first six lines in the table), error rates of 10 % for false positive predictions and 5 % for false negative predictions were allowed. For beneficial establishment thresholds (second six lines in the table), error rates of 5 % for false positive predictions and 10 % for false negative predictions were allowed. Thresholds were evaluated using a Likelihood-Ratio-Test; the observed distribution is given in bold, the expected distribution in parenthesis. Analyses included data from all dates of all greenhouses monitored in 2014, in which the corresponding pest or beneficial was present, and were carried out for greenhouse areas (GHa) and complete greenhouses (GHc).

| **Threshold** | **Area** | **True negative** | **True positive** | **False negative** | **False positive** | **df** | **$\chi^2$** | **p** |
|---|---|---|---|---|---|---|---|---|
| >10 *TV* nymphs / plant (LM) | GHa | **28** (33) | **35** (36) | **7** (2) | **5** (4) | 3 | 3.478 | 0.355 |
| | GHc | **11** (12) | **20** (20) | **2** (1) | **2** (2) | 3 | 0.383 | 1.000 |
| >5 *TV* Adults / plant (LM) | GHa | **75** (78) | **0** (0) | **7** (4) | **0** (0) | n.a. | n.a. | n.a. |
| | GHc | **31** (32) | **0** (0) | **3** (2) | **0** (0) | n.a. | n.a. | n.a. |
| >10 *MP* / plant (LM) | GHa | **18** (22) | **17** (19) | **5** (1) | **4** (2) | 3 | 4.102 | 0.294 |
| | GHc | **9** (9) | **10** (11) | **1** (1) | **2** (1) | 3 | 0.387 | 1.000 |
| >80 % *EF* parasitism rate (LM) | GHa | **20** (18) | **4** (5) | **0** (2) | **1** (0) | n.a. | n.a. | n.a. |
| | GHc | **9** (8) | **2** (3) | **0** (1) | **1** (0) | n.a. | n.a. | n.a. |
| >80 % *EF* parasitism rate (GLM) | GHa | **16** (14) | **4** (9) | **0** (2) | **5** (0) | n.a. | n.a. | n.a. |
| | GHc | **6** (5) | **2** (6) | **0** (1) | **4** (0) | n.a. | n.a. | n.a. |
| >5 *MP* / plant (LM) | GHa | **12** (13) | **26** (28) | **2** (1) | **3** (1) | 3 | 1.500 | 0.769 |
| | GHc | **5** (4) | **13** (15) | **0** (1) | **3** (1) | n.a. | n.a. | n.a. |

n.a. = due to empty cells test not calculated

The threshold of ≥80 % parasitism rate, indicating established biological control, was reached 4 and 2 times in a greenhouse area or a complete greenhouse, respectively (Table 4). Most of the time, parasitism rate was below threshold. Prediction of ≥ 80 % parasitism rate by the GLM was insufficient with 5 and 4 false positive predictions for greenhouse areas and the complete greenhouses, respectively (Table 4). The LM showed only 1 false positive prediction for greenhouse areas and complete greenhouses (Table 4).

## Prediction accuracy of *Macrolophus pygmaeus* density on crop

Due to the relevance for application in practice, a LM was trained for the prediction of the complete population of *M. pygmaeus* (i.e. adults and nymphs) on plants (Table 3). Prediction of the predatory bug population density was accurate most of the time. In P-T-1, population build up in the early season was slightly overestimated in both areas and the complete greenhouse (Figure 4). Population peaks as well as population density in the late season were accurately predicted. In P-T-2, prediction was accurate for the population build up in the early season, but densities at late season were underestimated (Figure 4). In detail, the population peak in greenhouse area 1 was underestimated by about 2 – fold, and late season population densities were underestimated by about 3-6 – fold in the complete greenhouse and both areas. Prediction for the complete greenhouses reduced over- and underestimations as compared to predictions for single areas (Figure 4).

The date, at which control became established (i.e. ≥ 5 *M. pygmaeus* / plant), was accurately predicted in 50 % of the greenhouse areas and complete greenhouses, and predicted slightly delayed (2 weeks) in greenhouse area 1 of P-T-1 and for the complete P-T-2. In greenhouse area 2 of P-T-1 the establishment was predicted 6 weeks early, but also numbers on plant were already at 4 *M. pygmaeus* / plant at that time (Figure 4). Overall, prediction complied with the required accuracy (Table 4). Prediction of the damaging level (i.e. ≥ 10 *M. pygmaeus* / plant) was rather conservative, with predictions ranging from 6 weeks early to 2 weeks late in case of greenhouse areas in both greenhouses, and being 4 weeks early in the P-T-1 and 2 weeks late in the P-T-2 (Figure 4). Also prediction of the damaging threshold complied with the required accuracy (Table 4).

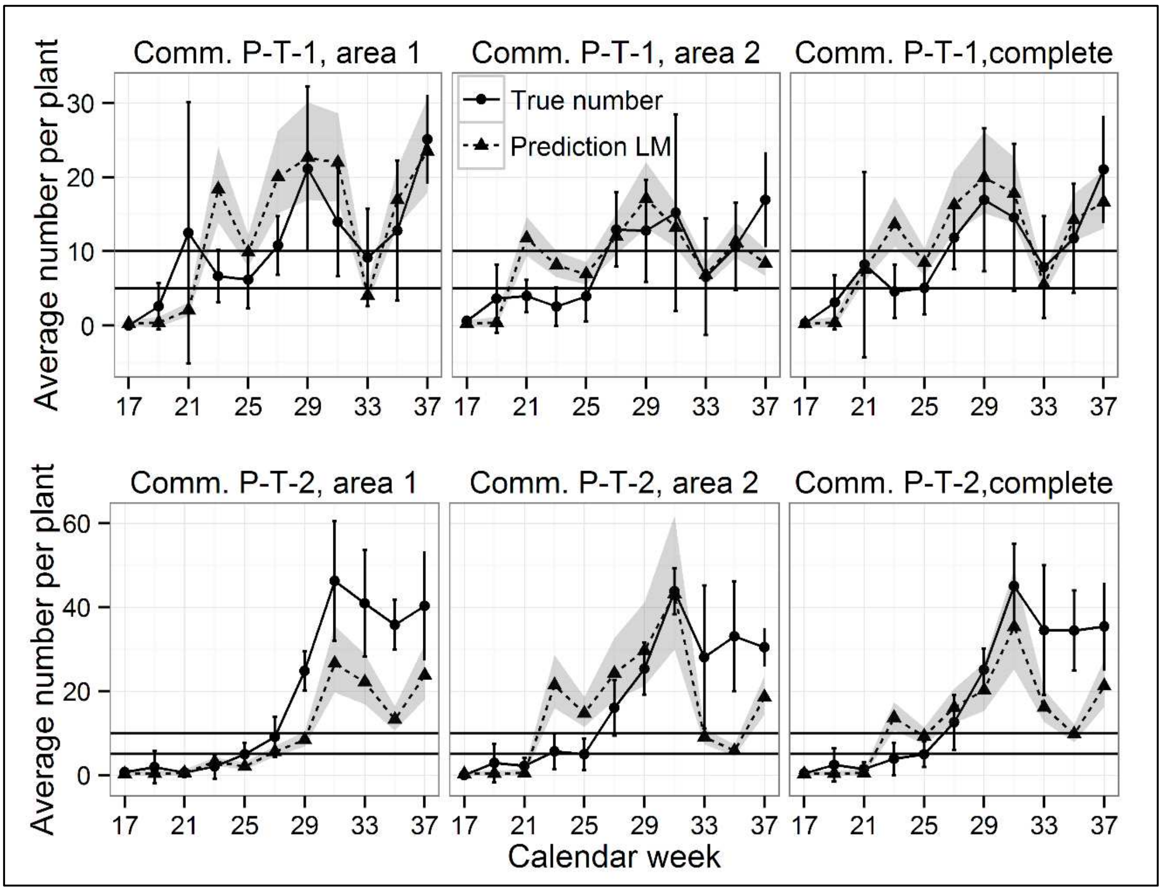

**Figure 4** Average number of *M. pygmaeus* adults and nymphs per plant in the Commercial Poly-Tunnel-1 and the Commercial Poly-Tunnel-2 calculated based on counts (True number), and predicted by a Linear Model based on adult trap catch (Prediction LM). A 95 % confidence interval is given (grey shade). A level for established control at >5 *M. pygmaeus* / plant as well as a tentative damaging level of >10 *M. pygmaeus*/plant are included (black horizontal lines). All estimates are given for each greenhouse area monitored by a single yellow trap and for each complete greenhouse based on the averaged count of all traps (P-T-3: N = 2; GH-1: N = 4). Predator counts per plant (i.e. on 9 leaves) were averaged based on all plants in the respective greenhouse area (4 plants per area) or the complete greenhouse (N = 8 for each poly-tunnel).

## Economic analyses of different beneficial regimes

Differences in the cost efficiency depended on the first occurrence of the pest in the crop. If pest became established early, i.e. in the greenhouses P-T-1 and P-T-2 (Table 2), costs were similar for the use of *M. pygmaeus* plus *E. formosa* in the early season (MP-save) and the use of *E. formosa* alone (EF-standard, EF-adapt) (Table 5).

Under these circumstances, the use of *M. pygmaeus* alone was about 1/3 more economic than any other introduction regime. If the pest enters late, i.e. in the greenhouses GH-1, GH-2 and GH-3 (Table 2), the use of *E. formosa* alone starting with detection of the pest (EF-adapt), was by far most economic, with at most times about 1/3 of the costs other introduction schemes implied (Table 5). Under these circumstances, EF-standard and MP-standard were similar in costs, whereas the combined use of both beneficials was most expensive. However, costs for monitoring and delivery were not considered.

**Table 5** Evaluation of product costs for biological control for different introduction schemes in all greenhouses monitored in 2014. The evaluations include costs for beneficials, artificial food and yellow traps. Costs were calculated based on the single package price indicated for commercial growers in 2014 by Katz Biotech GmbH (Baruth, Germany) and were extrapolated for each greenhouse area. Costs of work load for monitoring, introduction of beneficials or yellow traps and delivery of products were not considered (**MP standard**: *M. pygmaeus* only with 2 introductions of 0.5 individuals / m$^2$ plus *Sitrotoga* sp. eggs; **MP safe**: *M. pygmaeus* only with 2 introductions of 0.5 individuals / m$^2$ plus *Sitrotoga* sp. eggs plus 3 introductions of *E. formosa* with 1.5 individuals/m$^2$; **EF standard**: *E. formosa* only with introdutions every second week throughout growing season (until 4 weeks before end of season) with 3 individuals/m$^2$; **EF adapt**: *E. formosa* only, with introdutions every second week, begin 1 week after first pest detection (until 4 weeks before end of season) with 3 individuals / m$^2$)

| Greenhouse | Product | Costs MP standard (€) | Costs MP safe (€) | Costs EF standard (€) | Costs EF adapt (€) |
|---|---|---|---|---|---|
| **P-T-1 (300 m²)** | *M. pygmaeus* | 19.65 | 19.65 | 0 | 0 |
| | *Sitrotoga* sp. | 1.87 | 1.87 | 0 | 0 |
| | *E. Formosa* | 0 | 14.58 | 32.40 | 29.16 |
| | Yellow traps | 0 | 0 | 0 | 3.98 |
| | **Total** | **21.52** | **36.1** | **32.40** | **33.14** |
| **P-T-2 (300 m²)** | *M. pygmaeus* | 19.65 | 19.65 | 0 | 0 |
| | *Sitrotoga* sp. | 1.87 | 1.87 | 0 | 0 |
| | *E. Formosa* | 0 | 14.58 | 32.40 | 29.16 |
| | Yellow traps | 0 | 0 | 0 | 3.98 |
| | **Total** | **21.52** | **36.1** | **32.40** | **33.14** |
| **GH-1 (780 m²)** | *M. pygmaeus* | 51.09 | 51.09 | 0 | 0 |
| | *Sitrotoga* sp. | 4.86 | 4.86 | 0 | 0 |
| | *E. Formosa* | 0 | 37.91 | 101.09 | 42.12 |
| | Yellow traps | 0 | 0 | 0 | 9.54 |
| | **Total** | **55.95** | **94.67** | **101.09** | **51.66** |
| **GH-2 (700 m²)** | *M. pygmaeus* | 45.85 | 45.85 | 0 | 0 |
| | *Sitrotoga* sp. | 4.37 | 4.37 | 0 | 0 |
| | *E. Formosa* | 0 | 34.02 | 90.72 | 22.68 |
| | Yellow traps | 0 | 0 | 0 | 11.13 |
| | **Total** | **50.22** | **84.24** | **90.72** | **33.81** |
| **GH-3 (350 m²)** | *M. pygmaeus* | 45.85 | 45.85 | 0 | 0 |
| | *Sitrotoga* sp. | 2.19 | 2.19 | 0 | 0 |
| | *E. Formosa* | 0 | 17.01 | 45.36 | 7.56 |
| | Yellow traps | 0 | 0 | 0 | 4.77 |
| | **Total** | **48.04** | **65.05** | **45.36** | **12.33** |

# Discussion

## Prediction accuracy of *Macrolophus pygmaeus* density on crop

Prediction accuracy for population densities of *M. pygmaeus* on plants based on yellow trap catches was high with regard to fluctuation and level of true population development, for both, complete greenhouses and greenhouse areas (Figure 1). Predictions based on all traps within one greenhouse for the complete greenhouse were slightly more precise as compared to predictions for the different areas within one greenhouse. The latter may be explained by the high mobility of the predatory bug (Castañé et al. 2004) and its omnivorous and polyphagous feeding habits (Hillert et al. 2002; Castañé et al. 2011; Put et al. 2012). Hosts or prey of natural enemies are assumed to be generally distributed in discrete patches, and natural enemies must actively forage for their host or prey (Wajnberg et al. 2007). Also *T. vaporariorum* is known to be distributed highly aggregated (Noldus et al. 1986). However, because *M. pygmaeus* preys on several arthropods and feeds on plant materials as well, its distribution must not necessarily mirror the one of a single prey species. Also two studies of Athanassiou et al. (2003; 2005) showed aggregated distribution for the aphid *Myzus persicae*, but not for the adults of its natural enemy *Macrolophus costalis* (nymphs of the predatory bug were distributed similar to their prey). Such lack of spatial coincidence was also found for coccinelids preying on aphids, and for *Orius insidiosus* preying on corn silk flies, both in corn fields (Wagner and Ruesink 1982; Kalsi et al. 2014). For monitoring purposes, it can be assumed that the less aggregated the distribution of the target species, the less intensive the monitoring has to be in order to be meaningful (Taylor 1984; Noldus et al. 1986). This may explain the good correlations and predictions on *M. pygmaeus* shown in the current and in Chapter 2, with practice relevant trap densities and monitoring intervals (i.e. 51-74 traps / ha, fortnightly monitored). The high mobility on the other hand may have contributed to the slightly higher accuracy of monitoring in complete greenhouses as compared to greenhouse parts. That is, because parts of the population reflected in the trap catch in one area, may have left to another area at time of monitoring on plants.

The general good reflection of on-crop densities by trap catch may further be supported by the indifferent response of the predator to different trap colours and tomato leaves (Chapter 2). This unspecific response indicates that traps within the crop are mainly encountered by chance, because the predator searches actively for prey throughout the season, resulting in a constant chance of trapping *M. pygmaeus*. Also, this predatory bug is active at night and daytimes (Perdikis et al. 2004), indicating that influence of light intensity and to some extend also temperature can be regarded to be quite low. However, we found some tendency of increased trap catch on blue as compared to yellow traps in the late season (Chapter 2). Hence, the chance to trap *M. pygmaeus* on a sticky trap seems to be mainly dependent on its population density, a perfect precondition for the prediction of on-crop population densities based on adult trap catch.

## Prediction accuracy of *Trialeurodes vaporariorum* density on crop

The monitoring preconditions for *T. vaporariorum* with yellow traps, is quite different as described for *M. pygmaeus*. First of all, the pest is an obligatory herbivore and as a result there is no need to leave a plant as long as leaf quality remains good. Because sucking of plant sap at moderate densities is non-destructive, leaf quality is rarely affected by the pest in commercial tomato cultures. As there is no need to search for new host plants, adult progeny of one egg clutch will remain in the near surrounding. Generally, distribution of *T. vaporariorum* can be assumed to be highly aggregated (Noldus et al. 1986). Furthermore, short distance dispersal is regarded to occur mainly near ground level (Gerling and Horowitz 1984; Byrne et al. 1986). Therefore the main flight activity on high plant level, at the position of the sticky traps, is triggered by disturbance of mature adults or by hatching in case of young adults, which start their adult life by searching for upper plant parts as a suitable food source (Martin and Dale 1989). Furthermore, light intensity and temperature are known to strongly influence flight of *T. vaporariorum* (Webb et al. 1985). The mentioned factors may differ during the season, and therefore their influence may have contributed to the low accuracy of trap catch as a predictor of pest density on the crop.

Additionally the sample interval of traps can play an important role for the correlation with on-crop population densities. For instance, in surveys of lady beetle, correlations could be established when counts were taken every second day, but not with weekly counts (Hoffmann et al. 1997; Musser et al. 2004). It seems likely, that a monitoring interval and area monitored by one trap should assure, 1) that the target species has enough time to be trapped in sufficiently high amounts and 2) that the adults trapped belong mainly to the same generation as the adults present on the crop. The fortnightly interval carried out in this study surely is sufficient to catch reasonable numbers of *T. vaporariorum* and *M. pygmaeus*. However, regarding adult lifetime, it is possible that only a small fraction of whitefly adults on crop correspond to the ones trapped, because adult lifetime is about 18 days at 22°C (Manzano and van Lenteren 2009). For the predator on the other hand, lifetime at 23°C is about 50 days, ensuring that most of the adults trapped correspond to the generation present on crop (Margaritopoulos et al. 2003). Hence the sampling interval may have attributed to the different prediction accuracies of adult pest and predator densities on crop. Another factor that may have lowered the accuracy of pest monitoring is that prediction was either done for the adult or the nymph stage. For the alate adults, we assume that monitoring quality was low, because adults of *T. vaporariorum* dispersed at the slightest disturbance if light intensity (and temperature) was high. On the other hand, a leaf full of adults can be easily turned and observed as long as light intensity (and temperature) was low. This difference, which was to lesser extend observed in case of *M. pygmaeus* adults, may account for a high error in adult sampling of *T. vaporariorum* on the crop. Nymphs on the other hand cannot be translated into trap catch directly, because the adult stage is caught on traps. It was shown in previous studies that a shift of nymph counts on plants by one week can enhance their correlation with adult trap catch (Kim et al. 1999; Böckmann et al. 2014). However, even though the population peaks were underestimated, reaching of damaging thresholds for nymphs was accurately predicted. Yellow traps can therefore in principal be used for decision making, as long as conservative thresholds are used.

As a result of the mentioned factors, the correlation established for the prediction of whitefly densities on crop was not valid for prediction of population peaks in the current study. The information content may be increased if further factors are included into the model, such as light intensity or plant maintenance and harvest schedule of workers. However, implementation of these factors would also limit the chance of application in practice due to the lack of availability or the effort of determining these factors. Also, more precise monitoring of nymphal stages, i.e. the inclusion of L1 and L2 nymphs or even egg numbers or egg clutch numbers may contribute to a more robust correlation between trap catch and pest densities on plants.

Additionally, early pest detection by yellow sticky traps was approved in all the greenhouses monitored from 2012-2014 (Böckmann et al. 2014; Chapter 2; data in current study not shown). The latter is the main trigger for introductions of *E. formosa* on demand, rather than preventive, for whitefly control. Therefore, curative introductions in greenhouse tomato can be considered to be save, as long as a suitable yellow trap monitoring is applied.

## Prediction accuracy of *Encarsia formosa* parasitism rate

For *E. formosa*, prediction of high parasitism rate was accurate in the current study as long as the linear model was applied (Figure 3, Table 4). Low rates were overestimated by that model, which did however not result in incorrect prediction of established control, i.e. parasitism rates above 80 % (Scholz-Döblin 2013). A drawback of the model remains the illegitimate prediction of parasitism rates above 100%. This effect can be corrected if a Binominal GLM is applied. However, the latter model further overestimated parasitism rate, resulting in inadequate prediction of the establishment of *E. formosa* (Figure 3, Table 4). Because datasets are still very limited, both models should be further refined and tested. For the moment and in spite of the mentioned drawbacks, the linear model is useful for prediction of the parasitoid establishment in commercial tomato greenhouses. In this context I'd like to quote Box and Draper (1987) reminding us that "all models are wrong; the practical question is how wrong do they have to be to not be useful". Apart of the practicality of the LM, the current study also validated the simple indicator of 6 parasitoids trapped per yellow trap and week for established control of the pest, introduced by Böckmann et al. (2014). For a fortnightly monitoring in the current study, levels of parasitism were always above 80 % when trap catch was ≥ 12 parasitoids, and were always below 80 % when less than 12 parasitoids were found per trap (data not shown). The threshold of 80 % parasitism rate, indicating established control, may therefore easily determined by growers using yellow traps, even without any supporting modelling software. The accurate prediction of the LM, but also of the fixed number of parasioids to catch support our previous hypothesis, that the steep increase of parasitoids trap catch is triggered by increased patch leaving of the parasitoids at high parasitism rates, together with the increased emergence of parasitoids from those patches (Böckmann et al. 2014). Influence of increasing parasitism rates on patch leaving of parsitoids are extensively discussed by Wajnberg et al. (2007).

## Economic analyses of different beneficial regimes

The economic evaluation of three well-established control regimes with standardized introductions and the control regime with monitoring-based introductions of beneficials to control *T. vaporariorum* in tomato greenhouses, showed the potential of cost reduction with adequate pest monitoring. In the greenhouses monitored 2014, *T. vaporariorum* was primarily detected in late summer in 3 of 5 greenhouses (GH-1, GH-2, GH-3; Table 2). For these houses, the use of only *E. formosa* triggered by first pest detection clearly pays off economically, regarding material costs (Table 5). If work load for monitoring would have been included in this evaluation, that picture might have changed. Although most authors consider sticky traps to be a very cost / time efficient monitoring technique (De Gooyer et al. 1998; Musser et al. 2004; Natwick et al. 2007; Pizzol et al. 2010), Naranjo et al. (1995) found that their use was up to 19.7 times more expensive as compared to leaf turn monitoring of *Bemisia tabaci* in cotton. However, unlike in cotton, additional expenditure of time in tomato greenhouses is considerably low, because workers have in any case to be regularly in the crop for maintenance and harvest. Also monitoring of *E. formosa* and/or *M. pygmaeus*, which can according to the present study be used to detect established control of the pest, includes relatively low workload. That is because in case of the parasitoid only 6 parasitoids have to be counted to know that introduction can be stopped. *M. pygmaeus* on the other hand is easy to distinguish by the naked eye, and is generally caught in relatively low numbers, for instance with a maximum of 53 and on average 11 ± 12 (mean ± SD) adults / trap in the current study. More importantly, due to the recent advances in automated counts of trap catches, the labour costs for regular monitorings can be considered to decrease drastically in future (Cho et al. 2008; Guarnieri et al. 2012; Xia 2012). We therefore consider the advances of a monitoring-based decision making as presented here to grow from an economical perspective in combination with automated counts of trap catches.

If the pest was established in the greenhouses early in the season, the use of only *M. pygmaeus* was clearly the most economic control measure. However, in one commercial poly-tunnel we tested if the use of the predatory bug alone was sufficient for pest control in the early season. After detection of the pest in both poly-tunnels, the grower agreed to use in one of the tunnel only the predatory bug (P-T-2) whilst in the other poly-tunnel (P-T-1) three introductions of *E. formosa* were carried out additionally (Table 2). As a result, markedly higher densities of the pest occurred in the P-T-2, and the grower decided later in that season to introduce *E. formosa* in order to control for the pest (Table 2). The pest pressure at that time (calendar week 27) was markedly different between greenhouses, with 50.88 ± 20.07 *T. vaporariorum* nymphs in P-T-2, and 4.63 ± 3.54 nymphs in P-T-1 (average count on 9 leaves / plant ± SD). Due to that striking difference, the use of *M. pygmaeus* alone cannot be recommended, without a monitoring that at least detects reliably the first pest occurrence, triggering additional introductions of *E. formosa*. However, further studies should confirm results of this case study.

# Conclusion

The use of sticky traps is standard in many field and greenhouse crops. However, to date the information content of this tool is not used to its full extend in practice. In this study we could show that a comprehensive, regular monitoring with acceptable work load, can be used to prediction the establishment of biological control in greenhouse vegetables. Furthermore it shows the potential of saving costs, when control measures are adjusted to the actual densities of pests and beneficials in the crop, as compared to standardized introduction regimes. Nevertheless monitoring schemes have to be validated for each pest, beneficial and crop. Strong attraction to trap colour is no guarantee for explanatory power of trap catch on densities on crop. Together with suitable decision support tools and the ongoing automation of monitoring routines, a more cost and resource effective pest control becomes possible.

# Chapter 4

# AEP: An automatic decision support software for integrated plant protection[2]

## Abstract

A decision support software for greenhouse plant protection has to meet several requirements in order to be accepted and applied by growers. It should comply with the different operational needs of growers and should be helpful for inexperienced growers but also optimize plant protection strategies for experienced ones. Additionally a large number of cultures and pests should be covered and implementation of new crops, beneficials, pests and insecticides must be easy. Also handling should be easy and time saving. All software parameters should be adaptable to grower specific needs. The program should not decide on the control regime but rather give recommendations and provide data storage to optimize plant protection strategies. Thereby learning effects are stimulated and motivation to adapt decision processes in plant protection practice is increased.

In this article we show the structure of a decision support software (AEP – **A**utomatische **E**ntscheidungshilfe für den integrierten **P**flanzenschutz unter Glas) and describe its functionality for the model system tomato (*Solanum lycopersicum*) – whitefly (*Trialeurodes vaporariorum)* – natural enemy (*Encarsia formosa*).

**Key words:** Decision Support System, Whitefly, *Trialeurodes vaporariorum, Encarsia formosa*, Plant Protection, Beneficials, Greenhouse

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[2] E. Böckmann and Meyhöfer, R. (2015) AEP – Eine automatische Entscheidungshilfe-Software für den integrierten Pflanzenschutz. Gesunde Pflanzen **67** (1) 1–10
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# Kapitel 4

# AEP: Eine automatische Entscheidungshilfe Software für den integrierten Pflanzenschutz[2]

## Zusammenfassung

Eine Entscheidungshilfe-Software für den Pflanzenschutz im Gewächshaus muss viele Voraussetzungen erfüllen um Akzeptanz und Anwendung in der Praxis zu erreichen. Ihr Nutzerspektrum sollte unterschiedliche betriebliche Voraussetzungen einbeziehen und sowohl Anfängern beim Einstieg in die Pflanzenproduktion helfen als auch erfahrenen Betriebsleitern Verbesserungsmöglichkeiten in den gängigen Bekämpfungsstrategien aufzeigen. Weiterhin sollte eine möglichst große Anzahl an Kulturen und Schädlingen von der Software abgedeckt werden und die Implementierung neuer Kulturen, Nützlinge, Schädlinge und Pflanzenschutzmittel (PSM) unkompliziert möglich sein. Die Softwarestruktur sollte einfach und zeitsparend in der Bedienung sein und alle Vorgaben sollten sich an die nicht immer optimalen Gegebenheiten der Praxis anpassen lassen. Idealerweise sollte es keine Software sein die Nutzer bevormundet, sondern eine elektronische Hilfe und Gedächtnis für einen optimierten Pflanzenschutz. Nur so kann beim Nutzer ein Lerneffekt generiert und eine Optimierung der Entscheidungen in der Pflanzenschutzpraxis erreicht werden.

In diesem Artikel diskutieren wir die Struktur einer Entscheidungshilfe-Software (**AEP** –**A**utomatische **E**ntscheidungshilfe für den integrierten **P**flanzenschutz

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[2] E. Böckmann and Meyhöfer, R. (2015) AEP – Eine automatische Entscheidungshilfe-Software für den integrierten Pflanzenschutz. Gesunde Pflanzen **67** (1) 1–10
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unter Glas) und erläutern seine Funktionsweise an dem Modellsystem Tomate (*Solanum lycopersicum*) – Weiße Fliege (*Trialeurodes vaporariorum)* – natürlicher Gegenspieler (*Encarsia formosa).*

**Stichwörter:** Entscheidungshilfe, Weiße Fliege, *Trialeurodes vaporariorum,* Pflanzenschutz, *Encarsia formosa*, Nützling, Gewächshaus

# Einleitung

Im Anbau von Gemüse unter Glas ist beim Pflanzenschutz der Nützlingseinsatz schon seit vielen Jahren ein erfolgreiches Standardverfahren (van Lenteren 2012). Auch im geschützten Zierpflanzenanbau wird der Einsatz von Nützlingen zunehmend zum Standard. Vor allem im integrierten Anbau (IPM) ist in vielen Kulturen dennoch der Einsatz von Pflanzenschutzmitteln (PSM) notwendig; sei es um die Nützlingswirkung zu unterstützen oder aber um andere Schädlinge zu bekämpfen, deren biologische Bekämpfung derzeit noch unzureichend ist (Albert et al. 2007). Die Anwendung von biologischen und chemischen Methoden in derselben Kultur stellt viele Betriebe aber vor große Herausforderungen. Betriebsleiter und Pflanzenschutz-Berater müssen festlegen, wann ein Nützlingseinsatz begonnen und welcher Nützling in welcher Menge ausgebracht werden soll. Nützlinge müssen bestellt und ihre Qualität beurteilt werden. Im weiteren Verlauf muss erkannt werden, ob ein Einsatz erfolgreich verläuft, oder ob gegebenenfalls zusätzliche Nützlings- beziehungsweise PSM-Einsätze erforderlich sind. Für letztere sollte erneut eine Erfolgskontrolle stattfinden, wobei nun zusätzlich die Auswirkungen auf bereits ausgebrachte Nützlinge beachtet werden müssen. Unerfahrenen Betriebsleitern werden diese Einschätzungen nicht immer fehlerfrei gelingen. Bei solchen mit langjähriger Erfahrung wiederum ist es möglich, dass vermeintlich erfolgreiche Verfahren beibehalten werden, obwohl man eventuell ein vergleichbares oder besseres Ergebnis mit geringeren Aufwandmengen (= Kosten) oder alternativen Verfahren erreichen könnte.

Um gartenbaulichen Produktionsbetrieben eine Entscheidungshilfe (Decision Support System = DSS) anzubieten wird im EU-Interreg Projekt „Gezonde Kas“ (Gesundes Gewächshaus) eine Software für den integrierten Pflanzenschutz entwickelt. Diese Entscheidungshilfe soll unter dem Namen „Automatische Entscheidungshilfe für den integrierten Pflanzenschutz (AEP)“ zunächst in der Praxis erprobt und später vermarktet werden. Das Konzept basiert auf Expertenbefragungen, Literaturdaten und eigenen Forschungsergebnissen. Bereits vor Saisonbeginn soll die Software Anwendern ein geeignetes Verfahren für das Monitoring, d.h. Überwachung des Befallsverlaufs, für die betreffende Kultur vorschlagen. Im Saisonverlauf wird dann anhand der im Monitoring erhobenen Daten die Populationsentwicklung von Schädlingen (und ggf. Nützlingen) überwacht und der sparsame und effiziente Einsatz von

Nützlingen bzw. PSM empfohlen. Die Sommerkultur von Tomate wurde als erstes Modellsystem in die Entscheidungshilfe implementiert. Diese Kultur wurde aufgrund ihrer geringen Anzahl an bedeutenden Schädlingen und den klaren Vorgaben zur Kontrolle von Schadarthropoden ausgewählt. Kontinuierliche Erweiterungen sind geplant.

## Methoden – Literaturrecherche – Datenbasis

Als Grundlage für die AEP-Software wurde eine Literaturrecherche durchgeführt, um die wesentlichen Einflussparameter auf die Bekämpfungsstrategien von Gewächshausschädlingen zu benennen. Die betrieblichen Bedürfnisse wurden darüber hinaus in Gesprächen mit der Praxis ermittelt und einbezogen. Eine Umfrage unter 17 Pflanzenschutzberatern und Nützlingsanbietern wurde durchgeführt, um weitere Grundlagen der Bekämpfung für die ersten Modellorganismen, *Trialeurodes vaporariorum* – *Encarsia formosa*, dem Hauptschädling und seinem wichtigsten natürlichen Gegenspieler in Tomate, zu ermitteln. Um Wissenslücken zu schließen wurden dann gezielte Experimente durchgeführt um 1) die nötige Anzahl von Gelbtafeln für ein aussagekräftiges Monitoring zu ermitteln 2) den Zusammenhang von Populationsdichten im Bestand und Tafelfängen zu untersuchen 3) Möglichkeiten zur Optimierung des Nützlingseinsatzes in Sommerkulturen aufzuzeigen (Böckmann et al. 2014).

## Geplante Software-Struktur

Die Software-Struktur gliedert sich in ein **Basismodul** und ein **Saisonmodul** (Abbildung 1). Das AEP-Basismodul wird vor der Saison vom Betriebsleiter bearbeitet und verlangt Eingaben zu betrieblichen Gegebenheiten (z.B. Gewächshausanzahl, Gewächshausgröße(n), Pflanzenanzahl, Pflanztermin, Temperaturregime, Zielkultur(en), Zielschädling(e)). Auf dieser Grundlage wird eine Empfehlung zum Pflanzenschutz für hinterlegte Kultur-Schädling-Kombinationen erstellt (Auswahl und Anwendungsintervall von Nützlingen, Stichprobengröße und Intervall des Monitorings von Schädlingen und Nützlingen). Der Betriebsleiter hat nun die Möglichkeit, diese Vorgaben zu übernehmen oder aber an seine Betriebsabläufe anzupassen. Zusätzlich wird, sofern aus der Literatur bekannt, eine Schadschwelle bezüglich der Schädlingsdichte vorgeschlagen. Im Normalfall ist das die wirtschaftliche

Schadschwelle (Economic Injury Level, EIL), also der Wert ab dem die Kosten einer Pflanzenschutzmaßnahme gegen den Zielschädling niedriger sind als der zu erwartenden Schaden (Meyer 2003). Ist keine Schadschwelle für den Zielschädling bekannt, oder bevorzugt der Betriebsleiter eine andere Schädlingsdichte, kann der Wert individuell angepasst werden. Dieser Wert dient als Referenz für die im AEP-Saisonmodul erstellten Empfehlungen. Eine (erwartete) Überschreitung führt zu Anpassungen der im AEP-Basismodul festgelegten Bekämpfungsstrategie (z.B. Nützlingseinsatz erhöhen). Nach Bearbeitung des AEP-Basismoduls erhält der Nutzer einen Übersichtsplan seiner Gewächshäuser aufgeteilt in Boniturfelder. Diese werden anhand der Gewächshausgröße und der optimalen Boniturdichte festgelegt. Nach erstmaliger Bearbeitung muss dieses Modul in zukünftigen Jahren nur noch angepasst werden, sofern Änderungen geplant sind (z.B. Kulturwechsel).

Nachdem die genannten Angaben gespeichert wurden gelangt der Anwender in das AEP-Saisonmodul. Hier werden im festgelegten Intervall die Boniturdaten zu Schädlingen und Nützlingen eingetragen. Wird eine Eintragung ausgelassen, fragt die Software diese Daten nachträglich ab. Ein Fehlen der Daten kann ebenfalls vermerkt werden. Boniturergebnisse können manuell als Zähldaten von Stichproben im Bestand, oder im Fall von farbigen Klebtafeln auch automatisch z.B. durch den Einsatz einer Scoutbox® (Cropwatch BV, NL) eingepflegt werden. Gleiches gilt für Temperaturdaten, die möglichst automatisch eingepflegt werden sollten, sofern eine Übermittlung der Daten an einen Server möglich ist (etwa über den zentralen Computer der Klimasteuerung im Gewächshaus oder über autarke alternative Systeme wie etwa ein WiSensys®-System (Wireless Value, NL). Alternativ kann die Temperaturführung des zentralen Computers der Klimasteuerung im Gewächshaus genutzt werden (Verwendung von Soll-Werten). Diese Werte werden dann unter Berücksichtigung der Außentemperaturen, d.h. frei verfügbare Wetterdaten aus dem Internet, korrigiert. Diese Korrektur ist gerade bei hohen Außentemperaturen erforderlich, da ein Gewächshaus durch Lüftung i.d.R. nicht unter die Außentemperatur gekühlt werden kann. Sind alle Werte erfasst werden dem Anwender in der Ausgabemaske (aufgeteilt in Gewächshaus, Kultur und Schädling) Warnungen angezeigt, z.B. wann und wo ein Schädling aufgetreten ist oder eine Schadschwelle überschritten wurde.

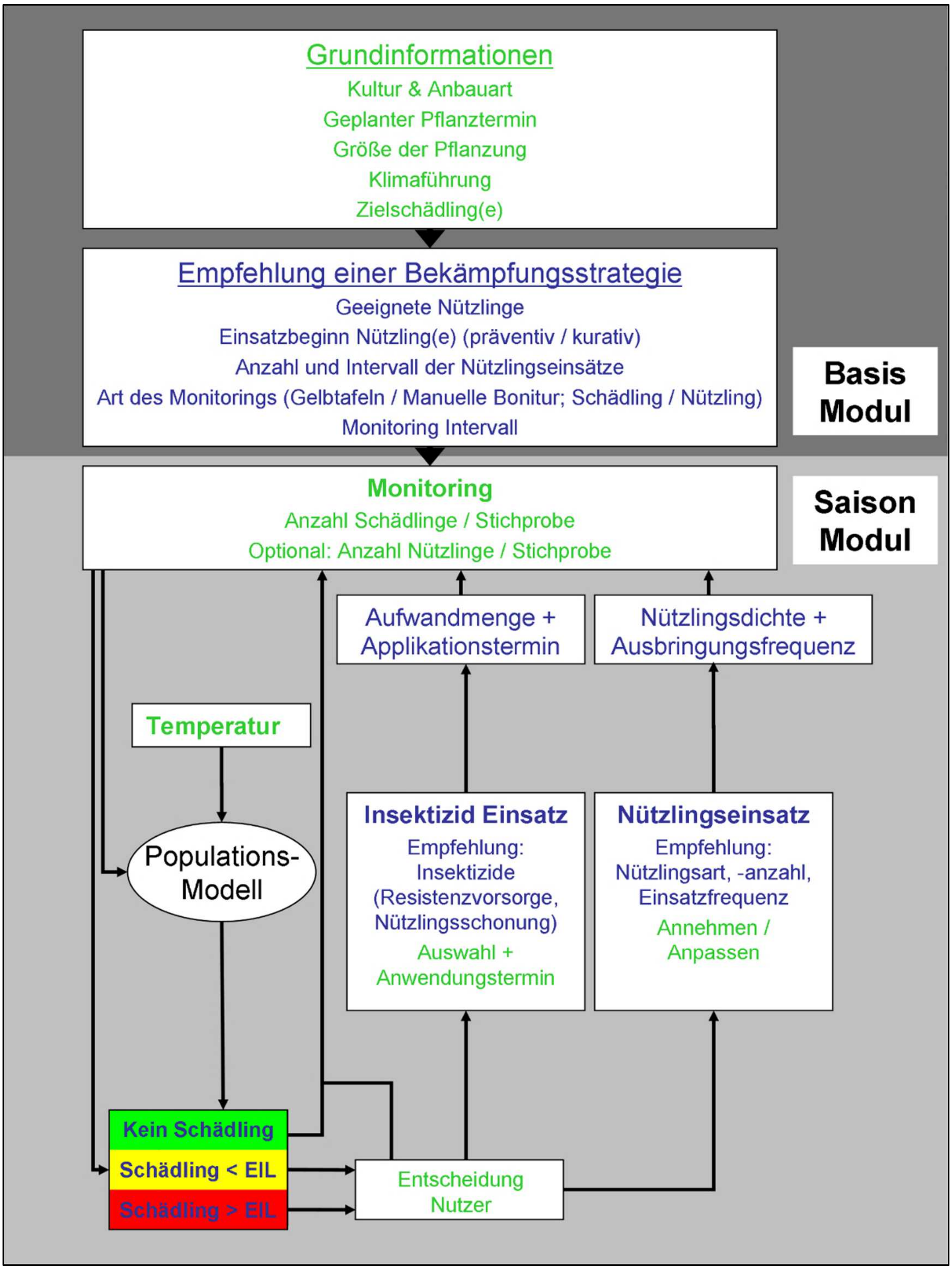


**Abbildung 1** Struktur und Nutzungsablauf von AEP. Grüne Schrift steht für Eingaben durch den Nutzer, blaue für die Ausgaben der Software und schwarze für systeminterne Abläufe. Pfeile mit durchgängiger Linie zeigen die Abläufe in der Software an, solche mit gestrichelter Linie geben zusätzlichen softwareinternen Informationsweitergaben wider. Die farbliche Darstellung der Befallssituation ergibt sich aus dem Abgleich der Schädlingsdichte zum Economic Injury Level (EIL). Grün bedeutet es sind bisher keine Schädlinge aufgetreten oder die Schädlingskontrolle durch Nützlinge ist optimal. Gelb zeigt eine Schädlingsdichte unter, rot eine Schädlingsdichte über dem EIL an. In beiden Fällen ist eine Anpassung der Bekämpfungsstrategie notwendig.

Diese Warnungen werden auf Basis von zwei Kontrollsystemen erstellt. Erstens werden die erhobenen Boniturdaten mit der im AEP-Basismodul festgelegten Schadschwelle abgeglichen. Dazu werden ggf. Monitoringdaten von Klebtafeln über Art- und Kulturspezifische Modelle auf die jeweilige Populationsdichte im Bestand umgerechnet. Zusätzlich wird die zukünftige Populationsentwicklung mit Hilfe eines Simulationsmodells auf Basis von aktuellen Populationsdichten und Wetterprognosen vorhergesagt. Befindet sich die aktuelle (bzw. vorhergesagte) Schädlingsdichte unterhalb der Schadschwelle, wird keine Warnung ausgegeben und der biologische Pflanzenschutz wird wie ursprünglich geplant fortgesetzt. Sind außerdem Nützlinge ausreichend etabliert, wird eine Beendigung des Nützlingseinsatzes empfohlen. Wurde eine Schadschwelle überschritten oder wird eine Überschreitung prognostiziert, generiert AEP eine Warnung und Empfehlung die Pflanzenschutzstrategie anzupassen. Der Nutzer kann diese Empfehlung umsetzen oder aufgrund der eigenen Einschätzung anpassen. Die Software empfiehlt bei (prognostizierter) Überschreitung der Schadschwelle in erster Linie einen erhöhten Nützlingseinsatz, wobei Einsatzdichte und -frequenz auf Basis der Anwendungsempfehlung von Nützlings-Produzenten ermittelt werden. Sind für die betreffende Kultur auch geeignete PSM zugelassen, so kann vom Betriebsleiter auch der Einsatz von Insektiziden ausgewählt werden. Bei der Empfehlung von PSM werden dabei zugelassene und nützlingsschonende Mittel bevorzugt. Wurden bereits PSM eingesetzt, so wird die Auswahl im Sinne der Resistenzvorsorge angepasst. Für die Anwendung werden geeignete Aufwandmengen sowie Wartezeiten für das erneute Betreten der Kultur und den nächsten Einsatz von Nützlingen angegeben. Waren Nützlings- oder PSM-Einsätze geplant, so bestätigt der Nutzer das alle geplanten Maßnahmen entsprechend umgesetzt wurden oder gibt entsprechende Abweichungen an. Diese Informationen werden wiederum abgespeichert und bei Prognosen durch das Simulationsmodell berücksichtigt.

## Nutzungsablauf am Fallbeispiel von *T. vaporariorum* im Tomatenanbau

Im vorliegenden Beispiel soll die Software AEP für ein Tomaten-Gewächshaus (1.000 m$^2$) eines biologisch arbeitenden Betriebes genutzt werden. Über die Willkommensmaske, die beim Öffnen des Programms erscheint, wählt der

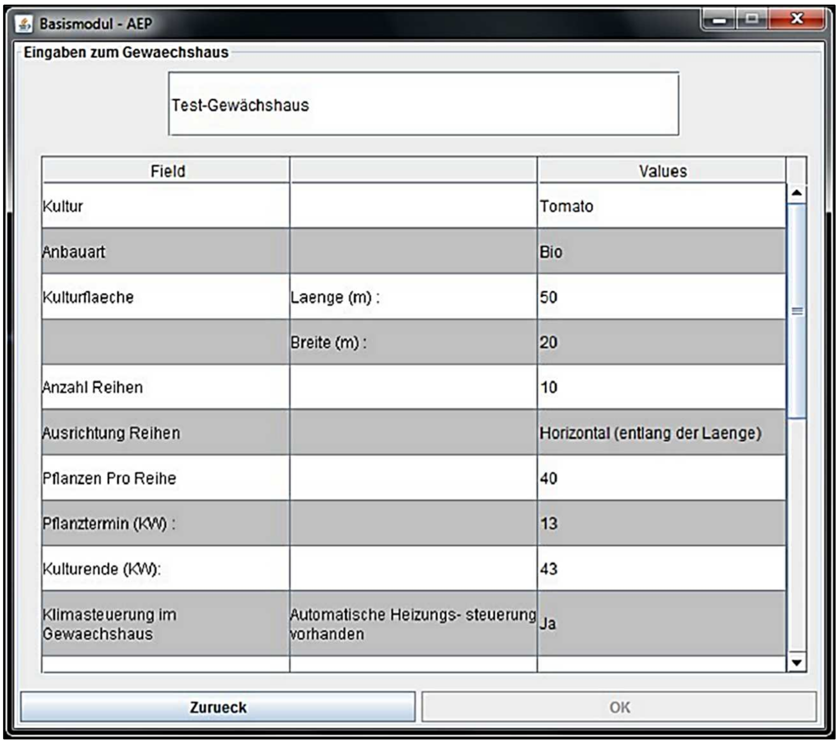
Nutzer zunächst das Basis-Modul aus (Abbildung 2). Dort werden die Basisdaten zur Kultur erfasst (Abbildung 3a, b). Zuerst wird Tomate als Zielkultur festgelegt. Um einen Übersichtsplan der Kultur anzulegen werden Länge (50 m) und Breite (20 m) der Anbaufläche sowie die Anzahl an Pflanzreihen (10), deren Ausrichtung (Horizontal) und die Pflanzenanzahl pro Reihe (40) eingetragen. In dem Beispielbetrieb wird in Kalenderwoche 13 gepflanzt und das geplante Kulturende liegt in Kalenderwoche 43. Es werden keine regelmäßigen Klimadaten an AEP gesendet. Somit werden die Soll-Temperaturen für den Klimacomputer genutzt (Tagestemperatur: 24°C; Nachttemperatur: 22°C). Der Gewächshausstandort wird angegeben, damit AEP Daten der nächstgelegenen Wettervorhersage abfragen kann um die Sollwerte gegebenenfalls zu korrigieren.

Willkommen in AEP, Ihrer Automatischen Entscheidungshilfe fuer den integrierten und biologischen Pflanzenschutz.

**Abbildung 2** Willkommens-Maske von AEP. Über anklicken der einzelnen Felder kann der Nutzer das AEP-Basismodul bearbeiten, aktuelle oder zurückliegende Boniturdaten im AEP-Saisonmodul eintragen, sich den Übersichtsplan mit den festgelegten Boniturfeldern anzeigen lassen oder das Ende der Saison eingeben. Die letzten drei Optionen stehen erst zur Verfügung, wenn das AEP-Basismodul bearbeitet wurde.

Der einzige regelmäßig auftretende Problemschädling in der Beispielkultur Tomate ist die Gewächshaus-Weiße Fliege, *T. vaporariorum*. Für Kultur und Schädling stehen in AEP die Nützlinge *Macrolophus pygmaeus*, *Encarsia formosa*, *Eretmocerus eremicus* und *Delphastus catalinae* zur Verfügung. Über Ausschlusskriterien wird von der Software der optimale Nützling wie folgt ausgewählt: *D. catalinae* wird erst bei hohen Schädlingsdichten empfohlen. AEP empfiehlt *M. pygmaeus* wegen der langen Zeit bis zur Etablierung (Katz Biotech AG 2014) nur bei Kulturzeiten > 9 Monate. Für die betreffende Kultur könnten also *E. formosa* oder *E. eremicus* genutzt werden, die Temperaturbedingungen passen für beide Nützlinge

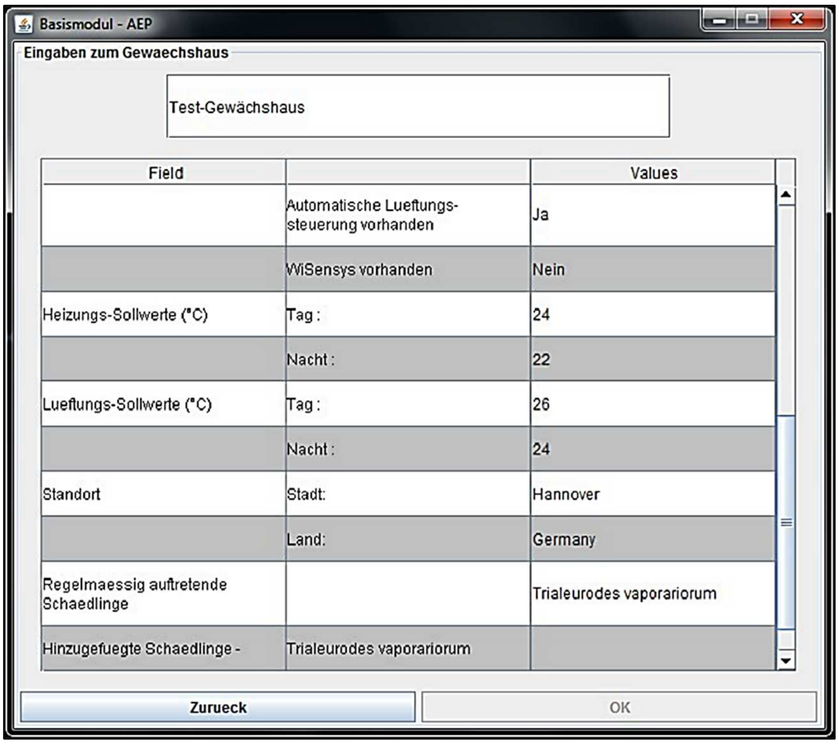
(Qiu et al. 2004). Aufgrund der hohen Variabilität von *E. eremicus* bei der Bekämpfung in der Praxis empfiehlt AEP diesen Nützling nur, wenn die Temperaturbedingungen für *E. formosa* nicht passend sind (Temperaturen > 30°C). Entsprechend wird die Ausbringung von *E. formosa* empfohlen (Abbildung 4).



Test-Gewächshaus

| Field | | Values |
|---|---|---|
| Kultur | | Tomato |
| Anbauart | | Bio |
| Kulturflaeche | Laenge (m) : | 50 |
| | Breite (m) : | 20 |
| Anzahl Reihen | | 10 |
| Ausrichtung Reihen | | Horizontal (entlang der Laenge) |
| Pflanzen Pro Reihe | | 40 |
| Pflanztermin (KW) : | | 13 |
| Kulturende (KW): | | 43 |
| Klimasteuerung im Gewaechshaus | Automatische Heizungs- steuerung vorhanden | Ja |

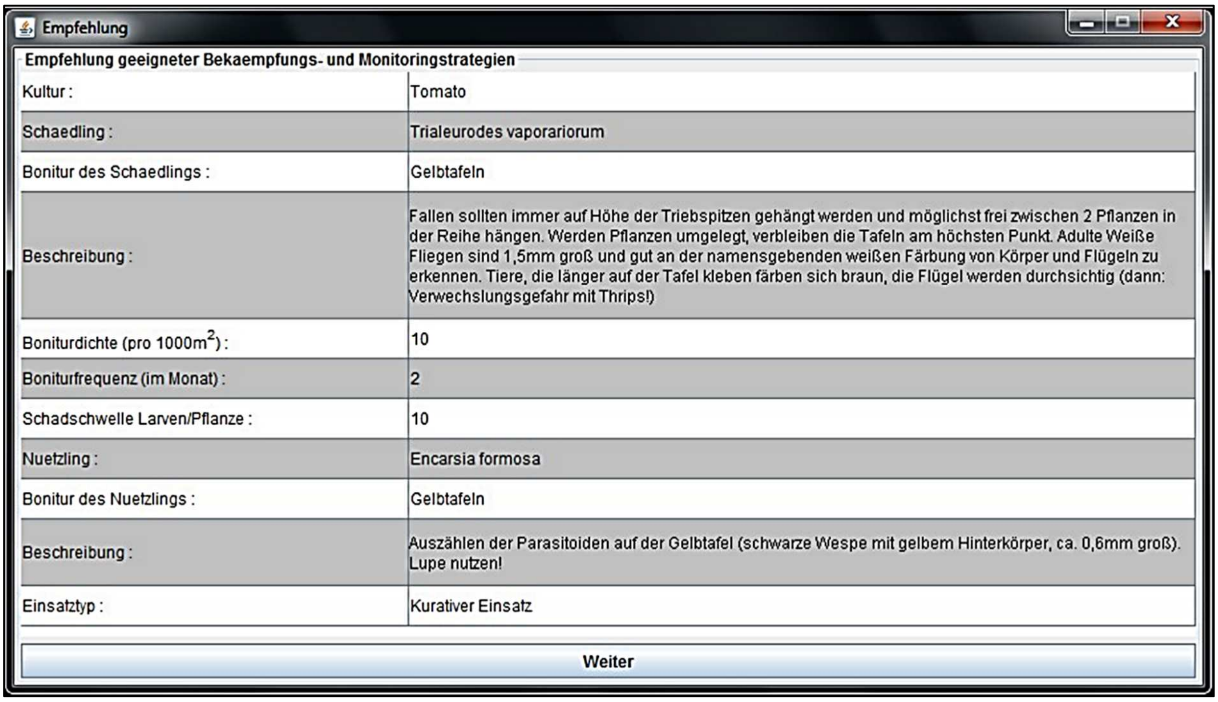
**Abbildung 3a**
Eingabemaske im AEP-Basismodul (Teil 1). Es kann ein individueller Name für das Gewächshaus (hier: Test-gewächshaus) vergeben werden und die dazugehörige Kultur wird ausgewählt. Die Anbauart entscheidet später über zugelassene PSM. Angaben zur Kulturfläche werden genutzt um einen Grundriss mit dazugehörigen Boniturfeldern zu erstellen (Abbildung 6b). Die Kulturzeit wird zur Auswahl geeigneter Nützlingsarten genutzt.



Test-Gewächshaus

| Field | | Values |
|---|---|---|
| | Automatische Lueftungs-steuerung vorhanden | Ja |
| | WiSensys vorhanden | Nein |
| Heizungs-Sollwerte (°C) | Tag : | 24 |
| | Nacht : | 22 |
| Lueftungs-Sollwerte (°C) | Tag : | 26 |
| | Nacht : | 24 |
| Standort | Stadt: | Hannover |
| | Land: | Germany |
| Regelmaessig auftretende Schaedlinge | | Trialeurodes vaporariorum |
| Hinzugefuegte Schaedlinge - | Trialeurodes vaporariorum | |

**Abbildung 3b**
Eingabemaske im AEP-Basismodul (Teil 2). Ist eine automatische Klimasteuerung vorhanden (Abbildung 3a), können Temperatur Soll-Werte für die Nützlingsauswahl genutzt werden. Über den Standort werden zusätzlich Daten der nächstgelegenen Wetterstation gesammelt, um in einer späteren Software Version ggf. die Temperatur-Sollwerte zu korrigieren. Für die angegebene Kultur (Abbildung 3a) werden nun die Schädlings-arten ausgewählt, die regelmäßig Probleme verursachen.



Empfehlung geeigneter Bekaempfungs- und Monitoringstrategien

| | |
|---|---|
| Kultur : | Tomato |
| Schaedling : | Trialeurodes vaporariorum |
| Bonitur des Schaedlings : | Gelbtafeln |
| Beschreibung : | Fallen sollten immer auf Höhe der Triebspitzen gehängt werden und möglichst frei zwischen 2 Pflanzen in der Reihe hängen. Werden Pflanzen umgelegt, verbleiben die Tafeln am höchsten Punkt. Adulte Weiße Fliegen sind 1,5mm groß und gut an der namensgebenden weißen Färbung von Körper und Flügeln zu erkennen. Tiere, die länger auf der Tafel kleben färben sich braun, die Flügel werden durchsichtig (dann: Verwechslungsgefahr mit Thrips!) |
| Boniturdichte (pro 1000m$^2$) : | 10 |
| Boniturfrequenz (im Monat) : | 2 |
| Schadschwelle Larven/Pflanze : | 10 |
| Nuetzling : | Encarsia formosa |
| Bonitur des Nuetzlings : | Gelbtafeln |
| Beschreibung : | Auszählen der Parasitoiden auf der Gelbtafel (schwarze Wespe mit gelbem Hinterkörper, ca. 0,6mm groß). Lupe nutzen! |
| Einsatztyp : | Kurativer Einsatz |

**Abbildung 4** Ausgabemaske des AEP-Basismoduls mit Empfehlungen für geeignete Bekämpfungs- und Monitoringstrategien im Test-Gewächshaus. Die Angaben zur geeigneten Boniturmethode, -dichte und –frequenz für *E. formosa* und *T. vaporariorum* werden in Böckmann et al. (2014) beschrieben. Geeignete Angaben zur Schadschwelle von *T. vaporariorum* waren in der Literatur nicht vorhanden. Die angegebene Schwelle wurde daher vorläufig festgelegt. Der kurative Einsatz von Nützlingen wird aufgrund des ausreichend genauen Monitorings des Schädlings empfohlen. Angaben zur Bonitur, zur Schadschwelle und zum Einsatztyp können vom Nutzer individuell angepasst werden.

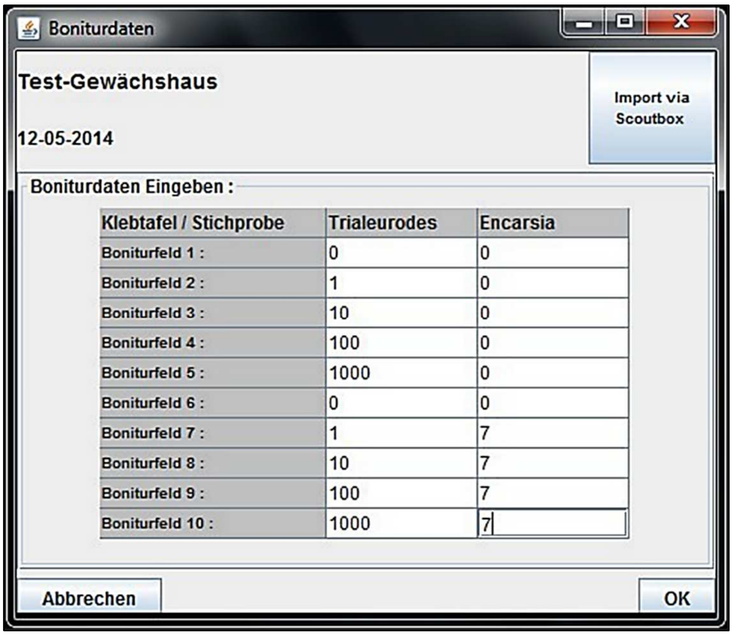
Da für *T. vaporariorum* keine praxistaugliche EIL bekannt ist (lediglich eine Ertragsminderung ab 70 Larven / 5cm² Blattfläche konnte von Hussey et al. (1958) ermittelt werden), wird von AEP als realistische, maximal tolerierbare Schädlingsdichte 20 Larven / Pflanze vorgeschlagen, d.h. diese Populationsdichte sollte während der gesamten Anbausaison nicht überschritten werden. Für ein geeignetes Monitoring empfiehlt die Software entsprechend der Ergebnisse von Böckmann et al. (2014 (in Druck)) den Einsatz von 10 Gelbtafeln für das 1.000 m$^2$ Gewächshaus (d.h. 1 Tafel pro 100 m²). Die Tafeln sollten wöchentlich auf *T. vaporariorum* kontrolliert werden. Wird das empfohlene oder ein engeres Raster gewählt, so wird der Einsatz von 3 *Encarsia formosa* / m$^2$ ab Erstauftreten der Weißen Fliege auf der Gelbtafel empfohlen (Scholz-Döblin 2013). Die Ausbringungen werden im 14-tägigen Intervall wiederholt. Entsprechend der Empfehlung von Scholz-Döblin (2013) kann ab einer Parasitierung von 80 % der *T. vaporariorum* Larven der Nützlingseinsatz beendet werden. Bei Verwendung von Gelbtafeln ist diese

Parasitierungsrate bei einer mittleren wöchentlichen Fangzahl von 6 Parasitoiden / Gelbtafel erreicht (Böckmann et al. 2014). AEP empfiehlt aufgrund der Zeitersparnis das Auszählen von Parasitoiden auf den Gelbtafeln anstatt der aufwendigeren Erfassung von Parasitierungsraten im Bestand.

Der Anwender hat nun die Möglichkeit diese Vorgaben zu akzeptieren, kann aber auch alle Vorgaben zum Monitoring, zur Nüzlingsauswahl und zur Schadschwelle an seinen Betriebsablauf anpassen. Wird aber vom Anwender z.B. eine geringere Tafelanzahl festgelegt wird die Aussagekraft des Monitorings verringert. In diesem Fall ist ein Nützlingseinsatz ab Erstauftreten des Schädlings zu unsicher und AEP empfiehlt zusätzlich einen präventiven Einsatz von 1,5 *E. formosa* / $m^2$ im Abstand von 14-Tagen, der ab dem ersten Erfassen des Schädlings auf 3 *E. formosa* / $m^2$ erhöht wird (Scholz-Döblin 2013). Im Folgenden gehen wir in diesem Beispiel aber davon aus, dass die ursprüngliche AEP-Empfehlung zum Monitoring (1 Gelbtafel pro 100 $m^2$, wöchentliche Bonitur) umgesetzt wird. Entsprechend wird das Gewächshaus automatisch in 10 Teilbereiche geteilt, die jeweils mit einer Gelbtafel überwacht werden. Das AEP-Basismodul ist damit abgeschlossen.

Mit Saisonbeginn startet der Nutzer das s.g. Saison-Modul, in dem die erhobenen Boniturdaten erfasst werden. Der Anwender bearbeitet dazu wöchentlich die Eingabemaske, indem er die Anzahl *T. vaporariorum* pro Gelbtafel eingibt (Abbildung 5). Im Anschluss an die Eingabe erscheint die Ausgabemaske 1 (Abbildung 6a). In dieser Befallsübersicht steht grün für Kulturbereiche in denen der Zielschädling (*T. vaporariorum*) noch nicht aufgetreten ist, d.h. kein Befall vorliegt. Ist der Schädling bereits aufgetreten und die Schädlingsdichte liegt unter der Schadschwelle ist die Farbdarstellung gelb. In diesen Kulturbereichen empfiehlt AEP dann einen Nützlingseinsatz. Ist dagegen die Schadschwelle überschritten ist die Farbdarstellung rot. In der Befallsübersicht entspricht der jeweilige Farbanteil dem Anteil an Kulturbereichen ohne (grün), mit moderatem (gelb) und mit hohem Schädlingsbefall (rot). Kulturbereiche mit moderaten Schädlingsdichten (gelb) werden wieder grün angezeigt, sobald eine ausreichende Nützlingsaktivität vorliegt. In grünen Bereichen werden keine weiteren Nützlingseinsätze geplant.

In der Befallsübersicht werden der aktuelle Befall und Maßnahmen zur Bekämpfung in allen Gewächshäusern bzw. Teilbereichen zusammenfassend dargestellt. Das dazugehörige Symbol zeigt an, ob ein gleich bleibender (N) oder erhöhter (N++) Nützlingseinsatz erforderlich ist.



Test-Gewächshaus

12-05-2014

Boniturdaten Eingeben :

| Klebtafel / Stichprobe | Trialeurodes | Encarsia |
|---|---|---|
| Boniturfeld 1 : | 0 | 0 |
| Boniturfeld 2 : | 1 | 0 |
| Boniturfeld 3 : | 10 | 0 |
| Boniturfeld 4 : | 100 | 0 |
| Boniturfeld 5 : | 1000 | 0 |
| Boniturfeld 6 : | 0 | 0 |
| Boniturfeld 7 : | 1 | 7 |
| Boniturfeld 8 : | 10 | 7 |
| Boniturfeld 9 : | 100 | 7 |
| Boniturfeld 10 : | 1000 | 7 |

**Abbildung 5**
Eingabemaske des AEP-Saisonmoduls. Links oben der Name des Gewächshauses (Testgewächshaus). Darunter das Datum der Bonitur. Oben rechts ein Button zum automatischen Hochladen von Boniturdaten via Scoutbox®. Die Boniturdaten werden automatisch oder von Hand für jedes Boniturfeld in die Tabelle eingetragen, aufgeteilt nach dem Zielschädling und dem zur Kontrolle eingesetzten Nützling. Die angegebenen Werte sind nicht praxistypisch, sondern wurden gezielt ausgewählt um die Entscheidungskriterien von AEP zu zeigen (siehe Abbildung 6a).

Der Anwender kann sich in einem zweiten Schritt den Plan des Gewächshauses anzeigen lassen um sich einen Überblick über die räumliche Verteilung des Befalls zu verschaffen (Abbildung 6b). Hier ist nun jedes Boniturfeld in der entsprechenden Farbe dargestellt.

Im nächsten und letzten Schritt zeigt AEP dem Nutzer die geplanten Einsatztermine, Einsatzbereiche und Einsatzdichten an (Abbildung 7). Der Anwender kann nun die Nützlinge bestellen und anschließend entsprechend der Vorgaben gezielt ausbringen. Wird das Saison-Modul einmal nicht in der geplanten Woche bearbeitet zeigt AEP alle zurückliegenden unbearbeiteten Termine an, so dass der Anwender ggf. Boniturdaten oder durchgeführte Pflanzenschutz-Maßnahmen nachtragen kann.

## Aktueller Entwicklungsstand der Software

Das Basis-Modul ist bereits fertig gestellt. Alle Grunddaten zu den Kulturbedingungen können aufgenommen und gespeichert werden. Boniturfelder werden automatisch errechnet und im Gewächshausgrundriss angezeigt. Für ein sicheres Erkennen der Zielschädlinge sowie der eingesetzten Nützlinge ist die zusätzliche Implementierung von Bildern und ausführlicheren Bestimmungshilfen vorgesehen. In der aktuellen Softwareversion sollte daher von unerfahrenen Nutzern die einschlägige Bestimmungsliteratur herangezogen werden.

**Abb.6a** Zusammenfassender Überblick zur aktuellen Befallssituation im Test-Gewächshaus auf Grundlage der eingegebenen Boniturdaten. Die Farbdarstellung repräsentiert die anteilige Befallssituation in den 10 Boniturfeldern (=Kulturbereichen) im Tomaten-Test-Gewächshaus (Abb.5). Rot bedeutet, dass die festgelegte Schadschwelle überschritten wurde unabhängig davon ob ein Nützling etabliert ist (Felder 4,5,9,10). Gelb zeigt die Detektion des Schädlings an, wobei die Schädlingsdichte unter der festgelegten Schadschwelle liegt (Felder 2,3). Grün steht für zwei unterschiedliche Befallssituationen: Erstens, dass kein Schädling gefunden wurde (Felder 1,6) oder zweitens, dass die Schädlingsdichte unter der Schadschwelle liegt und gleichzeitig der Nützling ausreichend etabliert ist (Felder 7,8). Das zusätzliche Symbol (N++) gibt an, dass aufgrund der Bekämpfungssituation teilweise ein erhöhter Nützlingseinsatz vorgesehen ist. Zur Veranschaulichung der Darstellungsweise wurde zusätzlich ein zweites Gewächshaus erstellt (Test-Gewächshaus 2). Die Einstellungen und Boniturdaten dieses Hauses werden hier nicht weiter behandelt. Über anklicken des Detail-Button gelangt der Nutzer zur nächst detaillierteren Darstellung (Abb.6b).

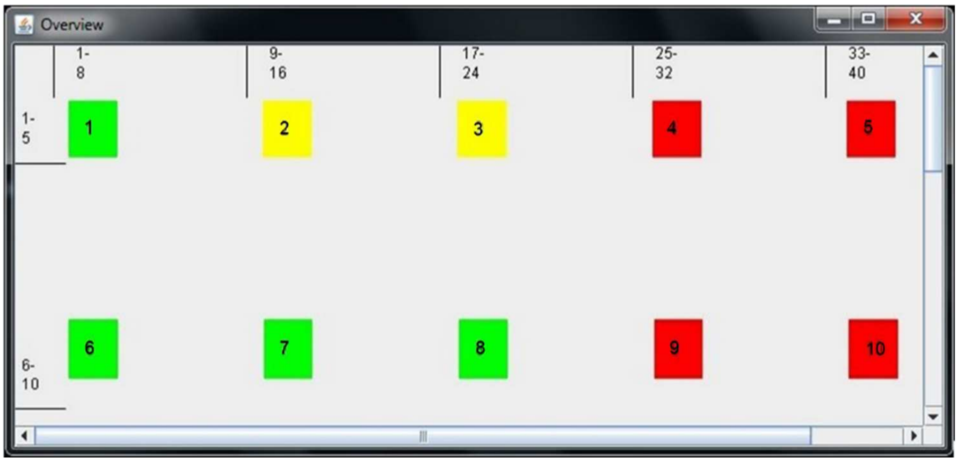


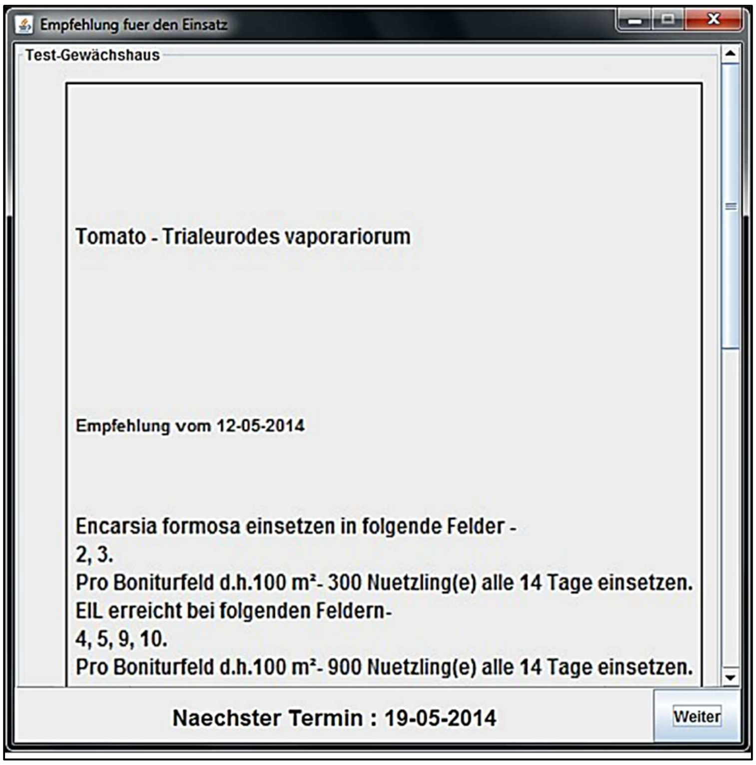
**Abb.6b** Überblick über die aktuelle Bekämpfungssituation im Test-Gewächshaus anhand der einzelnen Boniturfelder (=Kulturbereiche) im Gewächshausgrundriss. Zur Beschreibung der Lage der Boniturfelder dient die Angabe der ersten und letzten Reihe über die sich das Feld erstreckt (linker Rand) sowie der Anzahl an Pflanzen in der Pflanzreihe, die das Feld umfasst (oberer Rand). Das Boniturfeld Nummer 8 (Mitte unten) umfasst entsprechend die Pflanzen 17 bis 24 der Reihen 6 bis 10. Jedes Feld ist ca. 100m² groß und wird von einer Gelbtafel überwacht. Die Boniturfelder sind nummeriert um eine einfache Zuordnung bei der Eingabe der Boniturdaten (Abb.5) zu gewährleisten. Die Farbliche Darstellung wird entsprechend der in Abb.6a beschriebenen Regeln festgelegt.

Im Saison-Modul können Schädlings- und Nützlingsanzahlen manuell oder automatisch via Scoutbox® erfasst werden. Zurzeit ist die Nutzung aber nur für den integrierten Pflanzenschutz in Tomaten unter Glas und dem bedeutendsten Schädling, der Weißen Fliege, und ihren wichtigsten Gegenspielern realisiert. Allerdings greift das Programm auf eine Datenbankstruktur zurück, die leicht um weitere Kulturen, Schädlinge und Nützlinge erweitert werden kann. Für relevante Nützlinge wurde ein Ranking zu ihrer Eignung in Abhängigkeit von verschiedenen Faktoren (Temperatur, Tageslänge, Luftfeuchte und Kulturzeit), Einsatzdichten der Nützlinge in Abhängigkeit von der Schädlingsdichte (1. Präventiv, 2. Kurativ, 3. Hot Spot) sowie obligatorischen Kombinationen von Nützlingen hinterlegt. Für Bonituren von *T. vaporariorum* über Gelbtafeln ist ein Log-lineares Model hinterlegt, um von Fangzahlen auf Gelbtafeln auf die Schädlingsdichten im Bestand zu schließen (Böckmann et al. 2014).

Bei der Betrachtung der Bekämpfungssituation bietet AEP verschiedene Darstellungsformen an, wobei zuerst eine zusammenfassende Darstellung angezeigt wird (Befallsübersicht, Abbildung 6a). Alle detaillierten Darstellungsformen werden optional angeboten. Der Vorteil dieser Struktur liegt in der Übersichtlichkeit und Zeitersparnis für den Nutzer: sind keine Maßnahmen erforderlich oder wird keine detailliertere Betrachtung gewünscht, so kann das Saison-Modul in wenigen Schritten bearbeitet werden. Treten aber Probleme bei der Bekämpfung auf, so kann schon in der jetzigen Software-Version die Situation detailliert betrachtet werden um die Maßnahmen die AEP vorschlägt besser nachvollziehen zu können (Übersichts-Grundriss, Abbildung 6b). Weitere Darstellungen in Form von Liniendiagrammen zur bisherigen Populationsentwicklung sind denkbar aber zurzeit noch nicht verfügbar. Insbesondere für eine vergleichende Betrachtung des Bekämpfungserfolgs über verschiedene Jahre könnte diese Darstellungsform sinnvoll sein.

In Zukunft sollte es für den Nutzer auch möglich sein die Empfehlungen von AEP individuell anzupassen. Kommt der Nutzer z.B. aufgrund geringen Befalls zu der Überzeugung, dass die Situation noch keinen erhöhten Nützlingseinsatz erfordert, so sollte es möglich sein das bisherige Bekämpfungsregime bei zu behalten. Solche Anpassungsmöglichkeiten sind derzeit noch nicht implementiert, sind aber für die Praxistauglichkeit der Software unabdingbar. Weiterhin kann es passieren, dass es nachträglich z.B. durch Fehler oder

Verzögerungen bei der Bestellung und Lieferung von Nützlingen zu Verschiebungen bei der Ausbringung kommt. Auch in diesen Situationen muss dem Anwender die Möglichkeit gegeben werden die Abweichungen in AEP zu erfassen.



Tomato - Trialeurodes vaporariorum

Empfehlung vom 12-05-2014

Encarsia formosa einsetzen in folgende Felder -
2, 3.
Pro Boniturfeld d.h.100 m$^2$- 300 Nuetzling(e) alle 14 Tage einsetzen.
EIL erreicht bei folgenden Feldern-
4, 5, 9, 10.
Pro Boniturfeld d.h.100 m$^2$- 900 Nuetzling(e) alle 14 Tage einsetzen.

Naechster Termin : 19-05-2014

**Abbildung 7** Empfehlung für den nächsten Nützlingseinsatz entsprechend der festgestellten Bekämpfungssituation in den festgelegten Boniturfeldern (= Kulturbereichen) des Test-Gewächshauses. Am unteren Rand wird der nächste Boniturtermin angezeigt. Einsätze werden geplant für alle Felder in denen *T. vaporariorum* aufgetreten ist und *E. formosa* noch nicht ausreichend etabliert wurde (Felder 2, 3). Erhöhte Einsatzdichten des Nützlings werden für alle Boniturfelder festgelegt in denen die Schädlingspopulation die festgelegte Schadschwelle überschritten hat (Felder 4, 5, 9, 10). Für Boniturfelder in denen kein Schädling gefunden wurde ist kein weiterer Nützlingseinsatz vorgesehen. Das gilt auch für Felder in denen der Nützling etabliert wurde während gleichzeitig die Schädlingsdichte unter der Schadschwelle liegt.

Ein weiterer wichtiger Anwendungsbereich für den biologischen und integrierten Pflanzenschutz ist die Nutzung von Pflanzenschutzmitteln. Die Einbindung einer Datenbank ist geplant um aktuelle Zulassungsinformationen abzufragen. Anhand von weiteren Abfragen zur Persistenz und Nebenwirkung auf Nützlinge soll die Integrierbarkeit eingeschätzt werden und ferner ein Wechsel von Wirkstoffgruppen im Sinne einer Resistenzvorsorge berücksichtigt werden. Anhand dieser Kriterien wird eine Rangliste erstellt (geringe Nebenwirkung auf Nützlinge + ungenutzte Wirkstoffgruppe = hoher Listenplatz) und werden dem Anwender bevorzugte Pflanzenschutzmittel vorgeschlagen. Für ein gewähltes Pflanzenschutzmittel legt der Anwender dann den nächstmöglichen Anwendungstermin fest. Ist ein PSM-Einsatz erfolgt / geplant, wird die Persistenz des PSM von der Software bei der Planung eines erneuten Nützlingseinsatzes berücksichtigt.

Ein temperaturgesteuertes Simulationsmodell zur Populationsentwicklung von *T. vaporariorum* und *E. formosa* ist verfügbar, aber noch nicht in AEP implementiert. Klimaparameter und Wettervorhersagen, die eine Voraussetzung zur Einbindung und Steuerung für das Simulationsmodell sind, werden aber jetzt schon von AEP bereitgestellt.

# Diskussion

Die vorgestellte Software-Struktur soll den Nutzer nicht bevormunden, sondern ihn in seiner Entscheidungsfindung unterstützen. Der Anwender soll also alle Parameter flexibel an seine Bedürfnisse anpassen können, wird aber gleichzeitig auch auf die Folgen seiner Entscheidung hingewiesen. AEP warnt z.B. das ein weniger intensives Monitoring eine höhere Variabilität im Bekämpfungserfolg zur Folge hat. Dadurch wird ein Lerneffekt in Form einer Sensibilisierung für ein geeignetes Monitoringverfahren generiert. Wird ein Monitoring nicht entsprechend der Empfehlungen von AEP durchgeführt, etwa weil der Betriebsleiter das empfohlene Boniturschema in seinem Betrieb nicht leisten kann, so wird diese Unsicherheit bei der Empfehlung einer Bekämpfungsstrategie berücksichtigt. Nur durch die spezifische Erfassung dieser vom Nutzer festgelegten Anpassungen in AEP können diese Berücksichtigt werden. Auch kann es immer zu Verzögerungen in der Lieferung von Nützlingen kommen, was etwa im Populationsmodell berücksichtigt werden muss, um zu validen Aussagen zu kommen. Wir gehen davon aus, dass eine Entscheidungshilfe-Software, die ein optimales Vorgehen vorschlägt, sich aber dennoch an die gartenbauliche Praxis anpassen lässt, eine höhere Akzeptanz und somit auch eine stärkere Verbreitung erfährt. Ein hohes Maß an Flexibilität war daher erste Grundvoraussetzung und wurde bei der vorliegenden Struktur umfassend berücksichtigt.

Die Relevanz einer Entscheidungshilfe steigt aber auch mit ihrem Einsatzbereich. Daher war die zweite Grundvoraussetzung für unsere Entscheidungshilfe die einfache Implementierbarkeit neuer Kulturen, Schädlinge, Nützlinge und Pflanzenschutzmittel. Entsprechend wurden die zu erfassenden Basisinformationen auf ein Minimum reduziert. Sie umfassen aber dennoch alles, was als Grundlage für die Empfehlung einer Bekämpfungsstrategie nötig ist. So ist etwa die geplante Klimaführung entscheidend für die Auswahl eines geeigneten Nützlings und die Größe der Kultur bestimmt die benötigte Anzahl an Stichproben für eine aussagekräftige Bestandsüberwachung. Ursprünglich war geplant, auch das betriebliche Risiko eines Schädlingsbefalls im Bereich der Grundinformationen einzubeziehen. Zwei Gründe gaben letztlich den Ausschlag, dies nicht zu tun. Zum einen hätte es die Anzahl an Eingabeparametern im Basis-Modul und damit auch die Hemmschwelle zur Nutzung von AEP wesentlich erhöht. Zum anderen sind die Risikofaktoren Schädlingsspezifisch, was eine Implementierung neuer Schädlinge aufwendig gemacht hätte. Daher haben wir in der aktuellen AEP Version den Schwerpunkt auf ein aussagekräftiges und dennoch praxistaugliches Monitoring als Grundlage für eine effektive und kosteneffiziente Bekämpfungsstrategie gelegt. Dennoch ist geplant den bisherigen Softwaremodulen eine allgemeine Information zur Bedeutung ausreichender Gewächshaushygiene und zu typischen Risikofaktoren für Schädlingsbefall hinzuzufügen.

Nach einer Markteinführung von AEP könnte als ein weiteres Kontrollsystem der Abgleich von aktuellen und gespeicherten Populationsdaten von Schad- und Nutzarthropoden die Empfehlungen verbessern. Es wäre etwa denkbar, dass die Populationsverläufe, PSM-Einsätze und Schadschwellenüberschreitungen vergangener Jahre parallel zur aktuellen Entwicklung angezeigt werden. So könnten Betriebsleiter den aktuellen Bekämpfungserfolg besser einschätzen. Da diese Datenbank pro Saison und Betrieb z.B. bei Tomate nur um einen Datensatz wachsen würde ist der Nutzen in der Anfangsphase der AEP Nutzung stark beschränkt. Ein anonymisierter Austausch von Datensätzen einzelner Nutzer z.B. über einen Webserver wäre daher wünschenswert. Ohnehin setzt AEP einen Internetzugang des Rechners auf dem die Software läuft voraus, um den vollen Funktionsumfang zu nutzen. Solche Funktionen sind etwa aktuelle Listenabfragen (zugelassene Pflanzenschutzmittel) aber auch die Nutzung von Geräten zum automatisierten Einspeisen von Bonitur- und Klimadaten in AEP (z.B. automatische Erfassung und Zählung von Schädlingen (Scoutbox®, Cropwatch BV, NL), autonome Temperaturfühler (WiSensys® System, Wireless Value, NL) oder Temperaturdaten der Klimasteuerung im Gewächshaus) bis hin zur Bestellung von Nützlingen beim bevorzugten Produzenten. Eine Automatisierung dieser Abläufe wird sicher auch zur Benutzerfreundlichkeit und Praxistauglichkeit von AEP beitragen. Letzteres gilt besonders für große Betriebe. Während es bei der Temperaturerfassung noch denkbar ist mit der Solltemperatur für den Gewächshauscomputer zu arbeiten, ist das manuelle Auszählen und Einpflegen der Zähldaten von 100 und mehr Gelbtafeln in einem 1ha-Gewächshaus in der Praxis kaum zu realisieren. In unseren Pilotstudien haben wir daher autonome Funksensoren zur kontinuierlichen Temperaturerfassung im Bestand eingesetzt, die ihre Messdaten über eine Basis-Stationen mit GSM-Modem an eine Datenbank auf einem Webserver übermitteln können (WiSensys® System, Wireless Value, NL). Für das halbautomatische Monitoring von *T. vaporariorum* auf den Gelbtafeln wurde außerdem die Scoutbox® (Cropwatch BV, NL) genutzt. Codierte Gelbtafeln werden dabei mit Hilfe eines Rahmens in die Scoutbox® geschoben, in der ein hochauflösendes Gelbtafel-Foto aufgenommen wird. Nach Erfassung aller Gelbtafeln im Gewächshaus werden die Bilddaten über USB-Schnittstelle und einem internetfähigen Computer auf einen Webserver hochgeladen. Mit Hilfe einer Objekterkennungs-Software werden Schädlinge (zuverlässig derzeit für *T. vaporariorum*) auf dem Foto der Gelbtafel identifiziert, gezählt und gespeichert. Der ID-Code auf der Tafel ordnet die Zähldaten bestimmten Gewächshausbereichen zu und die Daten werden automatisch von AEP verarbeitet. Diese automatische Verarbeitung regelmäßig erhobener Daten mit zugeordneten Lageparametern verringert den Aufwand für den Nutzer in erheblichem Maße. Die Automatisierung gartenbaulicher Prozesse ist gerade in großen Betrieben zukunftsweisend und kann durch verringerten Arbeitsaufwand die Kosten in der Pflanzenproduktion senken. Ab einer bestimmten Betriebsgröße sollte die Verwendung von AEP daher mit weiteren Automatisierungen in der Datenerhebung einhergehen. In kleinen Betrieben ist die Nutzung der Software aber auch ohne weitere Automatisierung mit überschaubarem Arbeitsaufwand möglich. Eine Testversion der AEP soll in Kürze unter www.info-aep.de online verfügbar sein.

# General Discussion

Regarding arthropod monitoring in modern agriculture, there are at least two statements that most experts would intuitively agree on: First, that it is the Achilles heel of integrated pest management (IPM); Second, that it is rarely applied and interpreted to its full extent for decision making.

The main reasons behind this contradiction can be found in workload, knowledge gaps and conversion hurdles between research and practice. These factors do not stand alone, but are linked to each other. Monitoring has to pay off economically for growers in order to become accepted, and workload is often the main cost factor. Because workload is not much of an issue when monitoring is applied in research to answer scientific questions, the generated knowledge cannot be easily transferred into growers practice (Cullen et al. 2000). And if a monitoring fits the needs of practice, growers still need to know, how the information content achieved may be efficiently exploited to decide on pest control measures. In my thesis, I treated this complex of questions as whole, to gain the maximum profit for science and practice. Consequently, the aim of my work was to develop a comprehensive, low-cost monitoring approach, and to integrate it into a (software) tool, which enables growers to exploit and apply the information in a user friendly way for decision making.

The first step was to select a cheap and well accepted monitoring technique, which has the potential to be applied more efficiently. Manual counting of arthropods on the crop is a direct measure of their densities on the crop. It is therefore comprehensive, because all visible arthropods can be sampled, but it often also includes the highest workload (De Gooyer et al. 1998; Pizzol et al. 2010). Anyway, also plant assessments face limitation when it comes to pests that are hidden in plant tissue, stem or shoot, such as many Lepidopteran larvae. Also, many trap types are used for monitoring purposes, such as Berlese funnels, light traps, vacuum samplers and water traps (Jervis 2005). However, colored sticky traps, with or without additional attractants such as food or host odor and pheromones, are most commonly used in agriculture (Reynolds and Prokopy 1997; Nofemela 2010; Pinto-Zevallos and Vänninen 2013). The use of sticky traps is restricted to alate arthropods, but with the major exception of mites, many pests and natural enemies of importance comprise an alate adult stage (Albert et al. 2007).

For these reasons, sticky traps seemed to be a promising monitoring technique for my work; it remained the need to identify, if this technique comprises an additional informative value as compared to its typical application procedure. Traps baited with pheromone can generally be regarded to be selective, and often deliver only information about the target species. However, reviewing the literature one notices, that scientists commonly tend to optimize all kind of sticky traps for selectivity to the target pest (Gu et al. 2008; Döring et al. 2012; Sétamou et al. 2014), rather than recognizing and analyzing the by-catch as an information increment (Karut and Kazak 2007; Hoelmer and Simmons 2008). The reason behind is, that monitoring should not interfere with conservation of natural enemies in the crop. However, the latter risk will be restricted to mass-trapping approaches, where large numbers of natural enemies may be trapped (Van de Veire and Vacante 1984). However, even in the latter study, which combined mass-trapping of *Trialeurodes vaporariorum* with introductions of its parasitoid *E. formosa*, parasitism rates above 80 % were reached and therefore the applied trap densities of 1 trap / 6.2 m² did not interfere with establishment of biological control. Furthermore, for monitoring purposes, the implementation of natural enemies into monitoring routines is of high importance for decision making, and the lack of research on this topic is excessively discussed in literature (Binns and Nyrop 1992; Nyrop and Vanderwerf 1994; Musser et al. 2004; Hallett et al. 2014). This is the additional information content sticky traps can deliver for decision making, and it became the main focus of my work.

Because many natural enemies are attracted to colored sticky traps (Hoffmann et al. 1997; Hoback et al. 1999), their densities on crop can be estimated in the same way as done for the target pests. Also, many research article show that correlations can be established between arthropod densities on sticky traps and in the crop, but most of these articles lack a validation of these results by prediction of independent monitoring results, i.e. on data collected in a new season or at a different site (Gillespie and Quiring 1987; Higgins 1992; Naranjo et al. 1995; Kim et al. 2001; Macintyre-Allen et al. 2005). Taking into account that the establishment of a correlation of trap catch with populations on crop often takes a whole year, it may seem more attractive to gather results on related topics, even more when taking into account that validation of previous results may fail. But, if monitoring schemes should be of use, if they should be applied in decision making, validation of results becomes the most important corner stone of a study. Hence, in spite that I also felt the need to publish findings in advance, a validation was included as the final part of my work.

The reason that greenhouse tomato was chosen for my studies were that the pest spectrum in that crop is quite low, with *T. vaporariorum* being the most important pest in Germany (personal communication with growers and beneficial suppliers). Furthermore, control is mainly based on the introduction of the natural enemies, i.e. *Encarsia formosa* and *Macrolophus pygmaeus*. Pest and both natural enemies comprise an alate adult stage, and for *T. vaporariorum* and *E. formosa*, the attraction to yellow traps was known. The critic that I heard at one conference, that I actually focus on an easy problem is only true from a pest control perspective: the argument was, that *T. vaporariorum* is at most times well controlled by those natural enemies, whereas there are other pests, such as thrips or aphids in cucumber or eggplant, that are much more difficult to control. Therefore, I would like to clarify again that the purpose of this work was not to develop a new control approach for *T. vaporariorum*, but to optimize the existing approach in terms of IPM procedures and decision making for this pest.

In my thesis, I showed that for protected tomato culture, the information content of yellow traps can be exploited in much greater extent than currently done in practice. Regarding natural enemies of the greenhouse whitefly, *T. vaporariorum*, it was shown in the first chapter that parasitism rates above 50 % on the crop can be accurately indicated by trap catch of adult *E. formosa*. Most importantly, the indication of established control by the parasitoid, i.e. 80 % parasitism rate (Scholz-Döblin 2013), was accurately indicated by adult trap catch. In a similar approach, Hoelmer and Simmons (2008) did not find correlations between trap catches of the parasitoid *Eretmocerus emiratus* and parasitism of *Bemisia tabaci* nymphs on Cantaloupe and Watermelon. However, studies were carried out in open field and with horizontally placed traps, and did not consider correlations of trap catches with parasitism rate. Also Karut and Kazak (Karut and Kazak 2007) did not consider parasitism rates when they correlated trap catches of *Bemisia tabaci* with trap catch of *Eretmocerus lutea* in cotton. For decision making as defined in the IPM-concept, parasitism rate is what counts for growers. Information on the number of parasitized nymphs is no appropriate measure to indicate established control, because it does not include the pest density on the crop. On the other hand, the relation of parasitoid trap catch with the trap catch of a pest does not necessarily display the relations found on the crop. Therefore, I consider the focus on the correlation of parasitism rates with parastioids trap catch, as a strength of my study. Indications that both measures might correlate with *E. formosa* in protected tomato crop were found in literature (Van de Veire and Vacante 1984). The observation of the authors, that parasitoid trap catch increases markedly when parasitism rates are high was taken up in my work, was exploited in the context of monitoring, and was combined with the existing threshold level for established control (Scholz-Döblin 2013). The combination of the existing information with practice relevant monitoring schemes now enables growers, to optimize the introduction regime of *E. formosa* with minimal workload, by counting a maximum of 6 or 12 parasitoids caught per trap in 1 or 2 weeks, respectively. The accuracy of prediction of established control by the parasitoi, was confirmed in Chapter 3 of my work. To be discussed later, the implementation of the full established model into a decision support software combines this tool with others, and thus increases the practical relevance of this new monitoring approach.

For control of *T. vaporariorum*, two natural enemies are of major importance, including besides *E. formosa* the predatory bug *M. pygmaeus*. Therefore, in the second chapter of my work, a sticky trap monitoring of the predatory bug was tested. In contrast to *E. formosa*, information on colour attraction or on a density level indicating establishment of biological control by *M. pygmaeus* was lacking in literature. Therefore it was tested if *M. pygmaeus* adults were attracted to one of the commercial available and most commonly used trap colours, yellow and blue. Both colours showed only moderate attraction. A colour preference was neither found in a choice experiment with single adults, nor in a greenhouse study. With regard to colour preference, this study needs to be considered as a first screening, because additional factors such as sex of the adults and seasonal differences were not tested. It is somewhat surprising that *M. pygmaeus* does not prefer yellow before blue traps. That is, because the overall number of insects that prefer yellow is markedly larger than of those that prefer blue (Hoback et al. 1999; Johansen et al. 2011), and also the predatory bug *Orius similis* showd that preference (Raen et al. 2013).

Yellow traps reflect colour in the range of yellow-green (Natwick et al. 2007), and it can therefore be assumed that these traps are perceived as green leaves by insects. Hence, this colour could have been expected to play a role in orientation of *M. pygmaeus* to plants. A major difference between *M. pygmaeus* and most of the other species trapped on coloured traps is that its activity is not exclusively diurnal (Perdikis et al. 1999; Blackmer et al. 2004; Perdikis et al. 2004; Hamdan 2006; Gemeno et al. 2007). An adaption on light and dark conditions may have favoured the use of shape, rather than colour, for orientation. Nevertheless, colour vision at dark conditions was developed by primarily nocturnal animals, and is superior for object detection as compared to achromatic contrasts, because it defines properties of objects more reliable and constant (Kelber and Roth 2006). However, as opposed to *M. pygmaeus*, the Hawk Moths discussed in the latter study are highly adapted to nocturnal living.

With regard to monitoring of *M. pygmaeus*, in principal both trap colours seemed promising; I have selected yellow for further studies only because it enables furthermore monitoring of *E. formosa* and *T. vaporariorum*. Due to the moderate numbers caught on both trap colours in the greenhouse experiment, and taking into account the monitoring scheme applied, i.e. 1 trap / 100-200 m², monitoring does not interfere with biological control provided by the predatory bug or the parasitoid. In chapter 2 and 3 of my study, this assumption was confirmed by the successful establishment of the *M. pygmaeus* in all greenhouses where it was introduced, although a yellow trap monitoring was carried out. Also *E. formosa* reached sufficient parasitism rates as long as introduced alone; when both natural enemies where combined in one greenhouse, *E. formosa* was unable to establish, most likely due to intraguild predation by *M. pygmaeus*. Still, comparing the combined use with the introduction of the predatory bug alone in chapter 3, indicated a huge impact of the parasitoid on early season pest control. Similar results were found by Castañe et al. (2004), who also found that *E. formosa* population was eliminated by the predatory bug, but beforehand added to its biological control. The predatory bug showed also some preference for unparasitized *T. vaporariorum* and *Bemisia tabaci* nymphs as compared to those parasitized by *E. formosa* and *Eretmocerus mundus*, respectively (Castañé et al. 2004; Malo et al. 2012). Preference of predatory bugs for unparasitized hosts are likely caused by the increase in the lipid content of the host exuviae after parasitism, conferring greater resistance to mechanical penetration (Buckner et al. 2000). Therefore, the combined use of both parasitoids with Mirid bugs can be recommended for whitefly control, as done in Chapter 4 in the developed DSS AEP (Automatische Entscheidungshilfe für den Pflanzenschutz unter Glas). Currently, monitoring of predatory bugs is mainly based on direct counts on the crop (Isenhour and Yeargan 1981; Elkassabany et al. 1996). Growers consider a level of 3-7 *M. pygmaeus* nymphs and adults / plant as established biological control (personal communication with growers and beneficial suppliers). Because this predatory bug can potentially also cause damage on tomato crop, sometimes an additional damaging level of >10 *M. pygmaeus* is considered by growers (Joke de Jong, personal communication). That level is however not in line with results in literature, were damage is considered to rarely occur at densities, for instance at 50-300 *M. pygmaeus* / plant in one field study (Sampson and Jacobson 1999; Castañé et al. 2011). However, in my work I could show that both levels can be accurately predicted by the corresponding yellow trap catch (with 5 *M. pygmaeus* / plant as level for established control). Furthermore, not only densities of the adult, but also of nymphs and of the full population (i.e. nymphs and adults together) are accurately reflected throughout season by adult yellow trap catch. To my knowledge, this is the first time that such trap monitoring was established and validated for population development tracking of *M. pygmaeus* and for Mirid bugs in general. Regarding the moderate attraction to the traps, the good correlations are on first view surprising. The reasons behind may be found in the high mobility and the rather uniform distribution of predatory bugs in the crop (Castañé et al. 2004; Kalsi et al. 2014). It is an underlying principle, that the patchier a target species is distributed, the more intense a monitoring must be in order to estimate its population density (Taylor 1984). Because *M. pygmaeus* is not only polyphagous with regard to prey (Hillert et al. 2002), but furthermore feeds on plant sap and pollen (Castañé et al. 2011; Lykouressis et al. 2013), its distribution can be regarded to be quite independent from specific prey. Furthermore, Mirid bugs are known to be very active and strong flyers (Blackmer et al. 2004), with maximum flight durations of > 7 h and distances of > 90 km (Lu et al. 2009). Although Byrne (1999) challenged the concept to define whiteflies and small parasitoids as weak flyers that generally do not migrate actively, the distances these species typically fly, and hence their action radius, is much lower. For instance, *E. opulenta* was found to disperse 1 km within three generations and *E. inaron* dispersed 45 m in one generations, and only 6 % of whitefly *B. tabaci* adults flew more than 15 minutes in flight tunnel experiments (Byrne 1999; Liu et al. 2015). In the tomato monocultures studied, with rather constant climatic conditions, a relatively uniform distribution and the large action radius of *M. pygmaeus* likely added to a meaningful correlation of on-plant population with adult trap catch. The reliability of this correlation was confirmed in chapter 3 of my work, where the prediction based on the established correlation, was accurate for the full population of the predatory bug on crop.

In chapters 1, 2 and 3 of my work, also the pest species *T. vaporariorum* was monitored. For this species, the strong and specific attracted to yellow traps it is known from literature (Webb et al. 1985). In Chapter 1, numbers of *T. vaporariorum* adults found on traps were markedly higher than for its parasitoid *E. formosa*, even at high parasitism rates and hence tentatively high numbers of adult parasitoids on crop. The latter indicates a lower attraction of *E. formosa* to yellow traps as compared to the whitefly, which can be explained by the combined use of olfactory and visual cues for orientation by the parasitoid, as compared to a purely visual orientation of the whitefly (Byrne and Bellows 1991; Guerrieri 1997). Regarding attraction, the same is true for the predatory bug *M. pygmaeus*, and the reasons behind were already discussed above. Results on the possibility to correlate *T. vaporariorum* densities on crop with trap catch are conflicting, reaching from a density of 1 trap / 7 m² to 1 trap / 50 m² needed for accurate monitoring (Gillespie and Quiring 1987; Kim et al. 1999). In Chapter 1, it was shown that correlations can be established even with 1 trap / 170 m², with weekly monitoring interval. In Chapter 2, also monitoring with 1 trap / 100-130 m² and a fortnightly rating interval revealed meaningful correlations. In both studies, the estimation of nymphs on the crop by adult trap catch was more accurate as compared to adults on crop. One reason behind may be the more accurate sampling of nymphs on plants, because adults sometimes dispersed rapidly, depending on the light conditions, making continuous rating on plants difficult. *T. vaporariorum* was furthermore the only species, for which population peaks on crop were strongly underestimated by the prediction. The main reasons behind remain unclear, but it may be worthwhile to do more detailed assessments of nymph and adult populations on smaller scale, including all nymphal stages (i.e. not only the 3rd and 4th instar as done in the current study). Also the monitoring of plants may be adapted, for instance by assessing less leaves per plant, but including more plants into the assessment. That way the clumped occurrence of the pest could be covered more efficiently. However, also with the monitoring carried out in the current study, tentative thresholds could be adequately predicted for nymphal densities on crop in chapter 3. Also the first pest occurrence was reliably detected at all sites and in all three years of my study. Therefore, also the conclusion of Gillespie and Quiring (1987) was confirmed, pointing out that yellow traps used in practice relevant densities are reliable for detection of first occurrence of the pest. Because the first pest occurrence triggers the introduction of *E. formosa*, this information adds to the usefulness of the evaluated monitoring as basis for the Decision Support System (DSS).

One seemingly weakness of my studies is the low number of replicates that could be realized for each monitoring approach within the three years. One can however not compare the workload of the greenhouse experiments, which were carried out in this study, with experiments on laboratory scale. Furthermore, it has to be taken into consideration that the error, when translating from laboratory results under fully controlled conditions into more natural conditions, may be much bigger than the error resulting from lower replicate numbers under realistic conditions. I personally think therefore, that both approaches have their strength and weaknesses, depending on the research question. With regard to monitoring, I believe that research needs to take place in realistic areas and with natural populations; it is surely not enough to know that a species is attracted to a certain color and that it can fly over a certain distance, to estimate if a trap monitoring of insects located in commercial crops will be sufficiently exact, and which density and frequency of the monitoring is needed. For *T. vaporariorum* and *E. formosa*, most certainly enough basic information was available to investigate monitoring approaches directly under greenhouse conditions. In case of *M. pygmaeus*, where information from literature did not cover attraction to specific color, experiments under more controlled conditions were carried out to fill knowledge gaps.

Reviewing the current work, it attracts attention that I used relatively simple models, which include only the population density on the crop and the trap catch. However, during this study I also tested the inclusion of additional factors, such as time of assessment, i.e. calendar week, or weekly mean temperature (data not shown). The inclusion of the calendar week into the model resulted statistically speaking in higher explanatory power of the models for all species tested. The reason behind is that population density of all species increased with time after introduction or invasion, and hence also with increasing calendar week. The consequence was however, that the resulting model predictions did not anymore follow the population fluctuations of the respective arthropod, but increased rather linear with time. Hence, the objective of the monitoring, i.e. accurate predictions of the population dynamics, was hampered by the latter factor. Especially because of the need to see the failure of establishment of a beneficial or the decrease of a pest in decision making, it remains clear that a function which only increases is not useful for the purpose of population density prediction in IPM. The weekly mean temperature on the other hand, had no significant effect on the correlation, most likely because temperature in greenhouse tomato are relatively constant throughout the growing season, especially in heated glasshouses. Humidity on the other hand was not included due to the restricted reliability of the data loggers that were used in the current study. However, just as temperature, also humidity is typically controlled in a greenhouse environment, and tends to fluctuate mainly in a day-night, rather than a seasonal pattern. Still, inclusion of other factors such as light conditions or management of the crop could have resulted in more precise correlations for the one or other species, but these factors are complicated to assess (crop management) or no sufficient equipment was available for continuous assessment at all locations (light conditions). Furthermore, with focus on practical application of the results it remains clear that the more factors that need to be assessed for prediction of the target population densities, the less useful becomes a model for commercial growers. That is because more factors to assess mean more workload (if factors are assessed manually), and / or a need for more costs (if additional sensors are needed for assessments). Both increases the inhibition threshold of growers to apply a resulting DSS.

The main result of my study is, that the yellow trap, a well-known and often used tool in agriculture, can be used to monitor the whole complexity of a one pest, two natural enemies system (with the discussed limitations regarding the pest) in tomato crop. This finding has the potential to extensively optimize and fine-tune IPM in greenhouse tomato. As described in chapter 3 of my work, growers may now decide only by evaluating the trap catch, when to start and finish introductions of *E. formosa*, when to stop introductions of *M. pygmaeus*, and when *M. pygmaeus* itself might need to be controlled in the crop. These decisions do also apply for the combined use of the beneficials, optimizing early season control of *T. vaporariorum* with monitoring-driven introductions of *E. formosa* instead of standard use patterns. In case of *T. vaporariorum*, I believe that yellow trap monitoring is still useful as indicator for high pest pressure, but should go hand in hand with conservative thresholds, and it does not yet fully substitute additional samplings on plants.

The potential of economical savings of monitoring based decision making was shown in chapter 3, were the monitoring based decision of *E. formosa* introduction was most cost effective in all greenhouses, were the pest was detected late in the season. This was the case in 50 % of the commercial greenhouses monitored. Furthermore, also if the pest was present early, I found in chapter 1 that control in an experimental greenhouse became established after 5 introductions of 5 *E. formosa* / m². The costs for these introductions are about one third higher as compared to a combination of 2*0.5 *M. pygmaeus* / m² with 3*1.5 *E. formosa* / m² and *Sitrotoga* sp. eggs as additional food source (45.90 € and 29.89 €, respectively); they would however be comparable, when 3 *E. formosa* / m² would be applied, which is the final recommendation in our DSS (27.00 €; all calculations as described in chapter 3). However, if control is established with the same number of introductions when introducing 3 versus 5 *E. formosa* / m² was not tested. Until the latter is clarified, the decision if *M. pygmaeus* should be introduced in tomato greenhouses needs to be taken by growers, due to their experience when and if *T. vaporariorum* usually infests their crop. The growers I worked with had a quite exact estimation of this timing, and occurrence of *T. vaporariorum* was also found to be consistent in 4 of 5 greenhouses monitored in 2013 and 2014 (Chapter 3, Table 2). Because *M. pygmaeus* also provides some control on several other pest species (Hillert et al. 2002; Albert et al. 2007), growers may also consider the regular occurrence of aphids or leaf miners as a reason for its introductions. That the use of a DSS has high potential for reducing costs and material costs, mainly with regard to pesticide applications, was also shown in different other fields of crop management. For the use of fungicides, it was shown that the use of the DSS vite.net® in organic grape farming saved the growers an average of 195 € / ha / year due to reduced application of copper, relative to the usual farm practice (Rossi et al. 2014). Another DSS targeting fungal diseases of winter wheat reduced use and thereby also costs of fungicide in dry seasons (Jarroudi et al. 2015). Regarding fertilization of tomato crop, recommendations of the DSS VegSyst resulted in reductions of 34-65 % in fertilizer N (Gallardo et al. 2014). However, it remains clear that the use of a DSS, which is for pest, weed and fungal control typically linked to IPM, also induces costs. As compared to conventional pest control, under IPM, the cost savings from eliminating repetitive spraying frequently offset the cost of obtaining the information needed to guide the pest management program (Jones et al. 2010). These costs can potentially be reduced by DSSs, but their operation and manual assessment of parameters processed by the DSS also require labor time. For instance, 79.5 % of DAS users, a DSS for control of pests and diseases in tree fruit, perceived that its use resulted in improved timing of pest management, whereas only 13.4 % judged it to be cost saving (Jones et al. 2010). Nevertheless, the major advantages of DSSs are considered to be their potential to reduce material costs, workload and environmental risks due to reduction of pesticide use (Tardio et al. 2012) as well as use of beneficials. This potential was also shown for AEP (Automatische Entscheidungshilfe für den Pflanzenschutz unter Glas) in Chapter 4, but evaluation in more detail remains a major future topic and should include labor costs in small versus large greenhouses, as well as costs for manual versus automated monitoring of sticky traps.

In general, a DSS is a system which, through some combination of expert knowledge, databases and simulation models, support the user by providing recommendations on certain management options and / or allowing exploration of the consequences of making different decisions (Knight 1997). Hence, AEP is still somewhere between being an expert system and a true DSS, because no forecast of pest and beneficial development is included to date. However, simulation models are already available for all arthropods covered in this study, due to the extensive work of our colleagues Lia Hemerik and Maaike Wubs (University Wageningen). The future challenge will be to implement these models in AEP and further validate and refine them, especially when more data sets become available. Another important aspect for DSSs intended for use in agriculture is a grid based position awareness of predictions and simulations (Pontikakos et al. 2010; Stöckle et al. 2014). The latter is not only true for broad-acre crops, because also commercial greenhouses may to date easily reach 10 ha in size. Especially in such large greenhouses, mapping of distribution patterns of biological control is crucial for area-specific adaption of beneficial introductions. In Chapter 3 I could show, that the monitoring-based decisions must not be related to the whole greenhouse area, but can be related to greenhouse parts in the range of 100-200 m². Also, easy handling and good visualization of information is of high importance for adoption of DSSs in practice (Knight 1997). This topic is addressed in AEP by working with summarizing bar graphs and detailed mapping of the protection status in the crop. However, the visualization of every single area in AEP is sufficient for small, but not adequate for large greenhouses. In the latter, a future approach could be to apply models that automatically merge neighboured areas with similar control situation, resulting in recommendations for larger greenhouse areas. Similar approaches are used to identify homogenous land units in DSSs for precision farming (Stöckle et al. 2014). Besides of the mentioned desirable improvements, to date AEP cannot show the whole complexity of pest-beneficial and beneficial-beneficial interactions. For instance, to date only the growing period of tomatoes is decisive whether to use *M. pygmaeus* or not, and AEP recommends release in year-round cultures with growing season >9 month, in accordance with Scholz-Döblin (2013). But there are other aspects, which may favour the use of *M. pygmaeus*, such as the expected presence of other pests that are attacked by the omnivore predator. Hence, AEP does not yet reproduce the full complexity of decision making in tomato pest management, and needs to be further developed in this regard. However, most DSSs simplify the real conditions to some extent. Therefore DSSs can only provide recommendations, whereas the final decision has to be taken by the user (Longstaff 1994; Knight 1997). Although I am convinced of the usefulness of AEP, and I am very satisfied with the visualization of pest control status by the program, there remains the risk that it will not be widely applied by growers. The overall adoption of DSSs by growers is low as compared to the number of developed programs (Jones et al. 2010). Knight (1997) finds the reasons for this besides others in the academic environment where they were build, and the targeting of minor problems from a grower's perspective. Both statements are true for AEP: The program is the result of my PhD-Thesis, and *T. vaporariorum* can be controlled quite well without application of a DSS. To address this problem, we cooperated with two medium-sized companies, but to my opinion the chances of commercialization of AEP by these companies are low. To overcome these problems, the additional benefit of AEP, regarding optimization of IPM and the potential of cost savings, need to be communicated well to growers. Furthermore, its applicability needs to be broadened to other crop-pest-beneficial systems, and should at best also be combined with further DSS modules targeting other crop management decisions. In tomato for instance, there exist already several DSSs: VegSyst for fertilization and irrigation (Gallardo et al. 2014), TOMGRO for plant development and fruit production (Dimokas et al. 2008), FAST for diseases (Batista et al. 2006) and DIARES-IPM for identification of pests, beneficials, diseases, and nutrition deficiencies (Mahaman et al. 2003). Combining AEP with existing systems can increase the benefit for growers and thus their adoption of the resulting DSS. The latter would be in line with a general trend in todays' DSS conceptions, away from targeting a single part of the crop management, towards covering of all major decisions in cropping systems (Rossi et al. 2012; Rossi et al. 2014; Stöckle et al. 2014). Successful and broadly applied DSSs to date consider key aspects of crop production in a holistic manner, are web based and use wireless sensor techniques (Jones et al. 2010; Martin Tardio et al. 2012; Rossi et al. 2014; Stöckle et al. 2014). Hence, with its extendible modular structure and its interfaces to wireless sensors and automated monitoring tools, AEP comes with good prerequisites to become successfully marketed in future, but needs to be consequently developed further.

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# Curriculum Vitae

## Current employment

| | |
|---|---|
| 01.10.2014 – | Product Development Manager, Beneficials & Pollinators, Agronomic Development (Bayer CropScience AG, Monheim) |

## Employment history

| | |
|---|---|
| 01.02.2012 – 31.12.2014 | PhD Project: Development of a decision support software based on optimized monitoring in greenhouse plant protection (Leibniz University Hannover, Institute of Horticultural Production Systems, Dept. Phytomedicine; working group “Entomology”; team leader: Dr. Rainer Meyhöfer) |
| 01.05.2014 – 30.09.2014 | Plant protection consultant for vegetables and ornamentals, including monitoring as well as ordering and application of beneficials (Plant-Care, Hannover) |
| 01.09.2010 – 31.01.2012 | Research project: Bioengineering in cherry fruit fly control (*Rhagoletis cerasi* and *R. cingulata*) with reduced application of insecticides (JKI Dossenheim, Institute for Plant Protection in Fruit Crops and Viticulture; working group “Entomology in Fruit Crops”; Team leader: Dr. Heidrun Vogt) |

## University

| | |
|---|---|
| 01.10.2007 – 01.11.2009 | Study at the Ernst - Moritz - Arndt University Greifswald (Biology; main focus: Zoology, Animal Ecology, and Landscape Ecology & Nature Conservation) |
| 01.10.2003 – 01.10.2007 | Study at the Georg - August - University Göttingen (Biology; main focus: Neurobiology of Insects) |

## Stays abroad

| | |
|---|---|
| 01.03.2009 – 31.07.2009 | Laboratory experiments for the diploma thesis at the Instituto Valenciano de Investigaciones Agrarias (IVIA), Valencia, Spain |
| 15.09.2006 – 12.06.2007 | Internship at the University of Salamanca (Biology; main focus: Biological Control), Salamanca, Spain |
| 01.03.2007 – 31.05.2007 | Internship at the IVIA (Biological Control / Morphology of Parasitoids), Valencia, Spain |

# Publications

E. Böckmann and Meyhöfer, R. (2015)
AEP – Eine automatische Entscheidungshilfe-Software für den integrierten Pflanzenschutz
Gesunde Pflanzen 67(1), 1–10, doi: 10.1007/s10343-014-0332-y

E. Böckmann, M. Hommes and Meyhöfer, R. (2015)
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E. Böckmann, K. Köppler, E. Hummel and Vogt, H. (2013)
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E. Böckmann, T. Kersting and Heidrun Vogt (2012)
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Promising field and semi field results for cherry fruit fly control using neem
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E. Böckmann, J. Tormos, F. Beitia and Fischer, K. (2011)
Offspring production and self-superparasitism in the solitary ectoparasitoid *Spalangia cameroni* (Hymenoptera: Pteromalidae) in relation to host abundance
Bulletin of Entomological Research 102, 131-137, doi: 10.1017/ S0007485311000447

J. Tormos, F. Beitia, E. Böckmann, and Asís, J. D. (2009)
The preimaginal stages and development of *Spalangia cameroni* Perkins (Hymenoptera: Pteromalidae) on *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae)
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Microscopy and Microanalysis 15, 422–434, doi:10.1017/S1431927609090801