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BRIEF REPORT

Longevity of the whitefly parasitoid *Eretmocerus eremicus* under two different climate scenarios

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Abstract Whiteflies (Aleyrodidae) cause high economic losses in agricultural systems worldwide. Heavy reliance on insecticide use for whitefly control has led to the resistance development towards nearly all used groups of insecticides. A more sustainable, widely used, and irreplaceable control measure in protected cropping systems is biological control by augmentative release of parasitoids. All commercially available whitefly parasitoids are wasps from the genera *Encarsia* and *Eretmocerus*, with one of the most used parasitoid species being *Eretmocerus eremicus*. Biocontrol by these highly specialized natural enemies is sensitive to changes in environmental conditions. Ongoing anthropogenic climate change could affect multitrophic interactions between organisms, and biocontrol systems are not an exception. At the same time, little is known about the development of *E. eremicus* under projected future climate conditions. The present study evaluates the longevity of this important biocontrol agent by performing climatic chamber simulation driven by physically consistent, regionally downscaled, multi-model ensemble projections of the future climate for Luxembourg. Results show a reduction of its longevity up to 50% under future climate. The median survival in the projected future climate was found to be 13 days, which is 9 days less than under present climate. Implications on the efficacy of the whitefly biocontrol practices in future climate conditions are discussed.

Keywords Biocontrol · Future climate · Lifespan · Supplementary diet · Antagonist · Environment

Milan Milenovic and Matteo Ripamonti contributed equally to this work.

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Introduction

Whiteflies cause significant agricultural losses worldwide, both through direct damage by feeding on phloem sap, and indirect damage by excreting honeydew and vectoring viruses (Li et al., 2021; Fiallo-Olivé et al., 2020; Stansly & Naranjo, 2010; Byrne & Bellows Jr, 1991). *Trialeurodes vaporariorum* (Westwood) and *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) are the most economically damaging species, known for their invasions and associated virus outbreaks (Milenovic et al., 2019; Nasruddin & Mound, 2016; Boykin,

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2014; Cavalieri et al., 2014; Legg et al., 2014; Liu et al., 2012). Whiteflies are globally distributed, with Central Europe being on the northern edge of their range. Luxembourg is a good representative country for the climate of Central Europe, as it is located at its latitudinal midpoint.

Biological control is an indispensable tool in integrated pest management of whiteflies (Park et al., 2021; Horowitz et al., 2020; Rodríguez et al., 2019; Wang et al., 2018; Xie et al., 2018). In protected cropping systems, biocontrol relies mainly on augmentative release of parasitoid wasps and generalist predators, with *Encarsia formosa* (Gahan) and *Eretmocerus eremicus* (Rose and Zolnerowich) (Hymenoptera: Aphelinidae) currently being the most widely used and commercially available parasitoids. Biocontrol by parasitoids is strongly dictated by the climatic conditions, which are currently changing (Arias et al., 2021). Regional climate projections have advanced sufficiently to support climate change adaptation strategies in agriculture, especially when multi-model ensemble approach is applied (IPCC, 2021; Semenov & Stratonovitch, 2010; Tebaldi & Knutti, 2007). Today, a larger source of uncertainty in predicting the response of organisms to the changing climate comes from the lack of knowledge on the responses of the involved organisms (Tylianakis et al., 2008). Predictions of insect development in the future are based on experiments under constant conditions, but in nature environmental factors vary. A recent study used a climate chamber simulation to show that climate change will shorten the development time of the whitefly *B. tabaci* by almost half, potentially leading to faster population growth in the spring (Milenovic et al., 2023). Fitness parameters of its parasitoids are also directly influenced by abiotic factors (Zandi-Sohani & Shishehbor, 2011; Asplen et al., 2009; Qiu et al., 2006; McCutcheon & Simmons, 2001).

To understand the effectiveness of biocontrol methods in the future, simulations of future climate that consider daily changes in environmental factors are needed. Under these climate scenarios, several fitness parameters are trivial to describe the impact on these insects. In this preliminary study, we started with the longevity of adult *E. eremicus* parasitoids, one of the most important life-history traits for biocontrol agents (Plouvier & Wajnberg, 2018). This study aims to start closing this knowledge gap by using physical climatic chamber simulation to assess the longevity of the whitefly parasitoid *E. eremicus* in present and projected future climates.

Materials and methods

Two Bronson Incrementum 1400 and 1500 climatic chambers (Bronson Climate BV, The Netherlands) were used to simulate the present and the projected mid-term future (2061–2070) climate of Luxembourg, under RCP 8.5 (Supplementary Material S1), as described by Milenovic et al. (2023). Briefly, the climatic chambers were equipped with Valoya NS12 luminaries, set to deliver 480 μmol/m^{2}s photosynthetic photon flux density (PPFD) at 20 cm distance constantly during 12 daylight hours. The CO_2 concentration was maintained at 410 ppm and 700 ppm for the present and future conditions, respectively. The mean daily temperature for the present climate (2006–2015) was 19.8 °C, while the one for the future climate (2061–2070) was 23.4 °C. The mean daily relative humidity for the present climate was 69.2%, while the one for the future climate was 67.5% (Supplementary Material S1).

Parasitized *T. vaporariorum* nymphs were purchased (Koppert, Belgium), unpacked, and kept in glass petri dishes at room temperature (23 ± 1 °C) to facilitate the emergence. Adult parasitoids were kept for at least 2 h and no more than 24 h before being used for experiments. Approximately 50 unsexed adults and one 8 ± 3 mm cotton ball soaked in 300 μl diluted honey (50% *Robinia pseudoacacia* L. honey, 50% tap water) were introduced in mesh-capped glass vials (8 × 3 Ø cm) and placed inside the climatic chamber. An additional control vial was included in both climate experiments, containing non-soaked pressed cotton ball (no-food). A total of nine vials with honey and one no-food control vial were prepared per climate. The vials were placed in the two climatic chambers and dead individuals in each vial were counted daily on weekdays until no living individuals remained.

All statistical analyses were conducted using R software v 4.1.2 employing methodology as described by Ripamonti et al. (2022) with slight modifications. Individuals that died in the first 24 h of the experiment were excluded from analysis as this mortality is likely a result of their manipulation. *E. eremicus* longevity was estimated through Kaplan-Meier estimates. Generalized Additive Cox Model was applied with Peto's correction for ties and experimental replicates stratified. Covariate (climate and diet) effects were graphically represented by Aalen's Additive Regression Model (package 'survival', function 'aareg'; Supplementary Material S2) (Therneau, 2022). Vial identity was added to the model as a random effect. GAM results were subjected to EMMs comparisons (Lenth, 2022), with Tukey's p-value adjustment and all-pairwise comparisons (Hothorn et al., 2008). Summary statistics table was produced and paired with the results from all pairwise comparisons. The data that support the findings of this study are openly available in OSF at https://osf.io/qwsza/ (DOI: https://doi.org/10.17605/OSF.IO/QWSZA), while the complete R code for data analysis is publicly available at https://github.com/matteo-rpm/papers.

Results

Survival time analysis showed significant differences between *E. eremicus* adult longevity in the two climatic conditions. Future climate significantly shortened *E. eremicus* survival: the median survival time of the adults was 13 days, e.g. almost half of the 22 days survival observed in present climate (Table 1; Fig. 1).

A percentage of 75% of the adult parasitoids under future climate conditions died earlier (Q3, 14 days) than the 25% most short living adults under present climate conditions (Q1, 17 days) (Table 1). The most long-living specimen survived 18 days in the future climate, while the two most long living parasitoids survived 35 days in the present climate conditions. The individuals in the no-food control in both climate conditions had the shortest lifespan: the median survival time was only 2 days in future climate and 3 days in present climate (Table 1).

Discussion

The impact of climate change on survival of whitefly parasitoid *E. eremicus* is appraised here for the first time. The present study assesses the longevity of adults emerged from purchased parasitized nymphs, as representative tool of augmentative biocontrol practices. The results show severely reduced longevity in future climatic condition of Luxembourg (RCP 8.5) and likely in the one of all Central Europe. Three quarters of parasitoid individuals reared in future climate conditions lived less than 14 days after emergence. In comparison, under present climate conditions, the same mortality (75%) was reached only after 30 days, with an average longevity being more than twice longer than in the future condition experiment. At 14 days after emergence, when the future climate-reared insects reached 75% of mortality, only 25% of the present climate-reared parasitoids were dead. An overall accelerated development is to be expected: Qiu et al. (2004) and Gerling (1966) reported longer survival of the parasitoid at lower temperatures both in the presence and absence of the host. Although the mentioned authors employed a method of

Table 1 Summary statistics for *Eretmocerus eremicus* survival under present (2006–2015) and future climate conditions (2061–2070), measured as days between adult emergence and death

Climate	Diet	n	Mean [days]	Median [days]	IQR [days]	Q1 [days]	Q3 [days]	Pairwise comparisons
present	honey	538	22.1	22	13	17	30	a
future	honey	576	11.2	13	6	8	14	b
present	no food	47	3.7	3	3	2	5	c
future	no food	42	3.2	2	1	2	3	d

IQR: inter-quartile range; Q1: first quartile; Q3: third quartile. Comparisons between rows were conducted after a General Additive Model (GAM) with Cox Proportional Hazard family. Post-hoc comparisons were conducted with least-square means method and Tukey method for p-value adjustment at a significance level of 0.05 and represented by letters for every significant group. GAM and post-hoc details are reported in the Supplementary Material S2

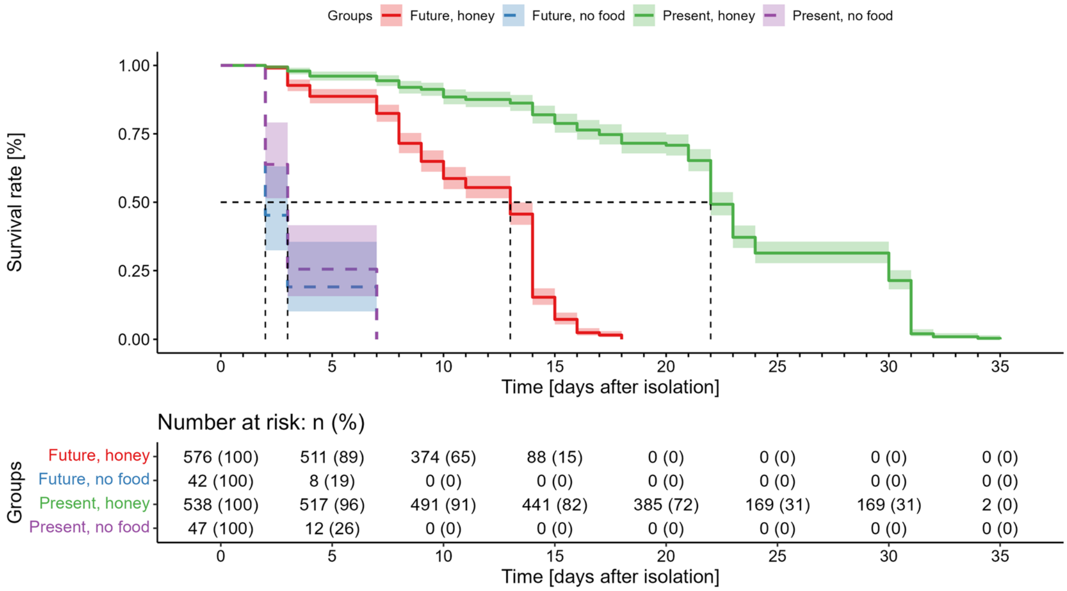

Fig. 1 Survival curves (Kaplan-Meier estimates) for adult *Eretmocerus eremicus* under present (2006–2015) and future climate conditions (2061–2070). Groups are divided based on climate (present vs. future) and diet (honey vs. no-food control). Risk table is reported, with the number of residual alive adults and percentage of total adults in parentheses

fixed constant temperatures, unspecified relative humidity, and uncontrolled CO_2 concentration, some comparison between their results and the present findings can still be made.

In the study of Qiu et al. (2004), *E. eremicus* adults lived for a mean of 38.4 days at 15 °C, 33.8 days at 20 °C, and 18.9 days at 25 °C, in absence of the whitefly host. In the work of Gerling (1966), *E. eremicus* lived for 40.5 days at 15.5 °C, and 8.6 days at 26.7 °C. In the present study we observed a mean longevity of 22.1 days in the present climate conditions (with 19.8 °C mean temperature), and 11.2 days at the future climate conditions (with 23.4 °C mean temperature). In comparison with Qiu et al. (2004) and Gerling (1966), a discrepancy can be observed, with *E. eremicus* living shorter in the present study. This suggests a generally shorter lifespan in the present study compared to the life table parameters obtained at constant conditions.

Furthermore, according to the work of Qiu et al. (2004), *E. eremicus* longevity in the presence of its host is 37–51% shorter at the same environmental conditions. This indicates that the longevity of this biocontrol agent, when in presence of its host, would be likely even shorter in the future than predicted by the present experiment.

Overall, the results show that future climate conditions will significantly affect *E. eremicus* lifespan, consequently reducing the timespan for parasitization, and possibly limiting its biocontrol capacity. Previous works (Qiu et al., 2004; Headrick et al., 1999; Powell and Bellows Jr, 1992) described *E. eremicus* lifetime parasitism in relation to age-specific fecundity and adult age as dependent on the temperature. Considering this, future climate may enhance the parasitization of whitefly nymphs (Aregbesola et al., 2019), but contemporaneously limit *E. eremicus* survival. The temporal limitation caused by the warmer climate may affect the capacity of controlling whiteflies in the future. Additionally, the development of the whitefly host will be shortened (Milenovic et al., 2023), resulting in faster population growth and a shorter release window for the parasitoid. This may require more frequent releases, increasing agricultural production cost. As the present results are focused solely on *E. eremicus* longevity without its host, further research is needed to predict the effect of the future climate in more detail, which includes parasitization rate and the development of preimaginal stages.

Author contributions Milan Milenovic, Matteo Ripamonti, Michael Eickermann and Carmelo Rapisarda conceived research. Milan Milenovic and Matteo Ripamonti conducted experiments. Jürgen Junk calculated present and future climate time series. Matteo Ripamonti and Milan Milenovic analyzed the data. Matteo Ripamonti and Milan Milenovic wrote the manuscript. All authors read, revised, and approved the manuscript.

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Data availability The data that support the findings of this study are openly available in OSF at https://osf.io/qwsza/ (DOI: https://doi.org/10.17605/OSF.IO/QWSZA), while the complete R code for data analysis is publicly available at https://github.com/matteo-rpm/papers.

Declarations

Competing interests The authors declare no competing interests.

References

Aregbesola, O. Z., Legg, J. P., Sigsgaard, L., Lund, O. S., & Rapisarda, C. (2019). Potential impact of climate change on whiteflies and implications for the spread of vectored viruses. *Journal of Pest Science,92*, 381–392. https://doi.org/10.1007/s10340-018-1059-9

Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M. D., Plattner, G. K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R. P., Armour, K., … Zickfeld, K., et al. (2021). Technical Summary. In V. Masson-Delmotte (Ed.), *Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 33–144). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.002

Asplen, M. K., Hardin, J. A., & Byrne, D. N. (2009). The relationship between pre-oviposition flight behaviour and reproductive timing in whitefly parasitoids. *Physiological Entomology,34*, 350–358. https://doi.org/10.1111/j.1365-3032.2009.00698.x

Boykin, L. M. (2014). Bemisia tabaci nomenclature: Lessons learned. *Pest Management Science,70*, 1454–1459. https://doi.org/10.1002/ps.3709

Byrne, D. N., & Bellows, T. S., Jr. (1991). Whitefly biology. *Annual Review of Entomology,36*, 431–457. https://doi.org/10.1146/annurev.en.36.010191.002243

Cavalieri, V., Manglii, A., Tiberini, A., Tomassoli, L., & Rapisarda, C. (2014). Rapid identification of *Trialeurodes vaporariorum*, *Bemisia tabaci* (MEAM1 and MED) and tomato-infecting criniviruses in whiteflies and in tomato leaves by real-time reverse transcription-PCR assay. *Bulletin of Insectology,67*(2), 219–225. (EID: 2-s2.0-84923282888).

Fiallo-Olivé, E., Pan, L. L., Liu, S. S., & Navas-Castillo, J. (2020). Transmission of Begomoviruses and other Whitefly-Borne Viruses: Dependence on the Vector Species. *Phytopathology,110*, 10–17. https://doi.org/10.1094/PHYTO-07-19-0273-FI

Gerling, D. (1966). Studies with Whitefly Parasites of Southern California: II. *Eretmocerus californicus* Howard (Hymenoptera: Aphelinidae). *The Canadian Entomologist,98*, 1316–1329. https://doi.org/10.4039/Ent981316-12

Headrick, D. H., Bellows, T. S., & Perring, T. M. (1999). Development and Reproduction of a Population of < i > Eretmocerus eremicus (Hymenoptera: Aphelinidae) on < i > Bemisia argentifolii (Homoptera: Aleyrodidae). *Environmental Entomology,28*, 300–306. https://doi.org/10.1093/ee/28.2.300

Horowitz, A. R., Ghanim, M., Roditakis, E., Nauen, R., & Ishaaya, I. (2020). Insecticide resistance and its management in Bemisia tabaci species. *Journal of Pest Science,93*, 893–910. https://doi.org/10.1007/s10340-020-01210-0

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in General Parametric Models. *Biometrical Journal,50*, 346–363. https://doi.org/10.1002/bimj.200810425

IPCC. (2021) Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate change 2021: The physical science basis. Contribution of working Group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3−32). Cambridge, United Kingdom and NewYork, NY: Cambridge University Press. https://doi.org/10.1017/9781009157896.001

Legg, J. P., Shirima, R., Tajebe, L. S., Guastella, D., Boniface, S., Jeremiah, S., Nsami, E., Chikoti, P., & Rapisarda, C. (2014). Biology and management of *Bemisia* whitefly vectors of cassava virus pandemics in Africa. *Pest*

Management Science,70(10), 1446–1453. https://doi.org/10.1002/ps.3793

Lenth, R. V. (2022). emmeans: Estimated marginal means, aka Least-Squares Means. R package version 1.8.0.https://CRAN.R-project.org/package=emmeans

Li, Y., Mbata, G. N., Punnuri, S., Simmons, A. M., & Shapiro-Ilan, D. I. (2021). Bemisia tabaci on Vegetables in the Southern United States: Incidence, Impact, and Management. *Insects,12*, 198. https://doi.org/10.3390/insects12030198

Liu, S., Colvin, J., & De Barro, P. J. (2012). Species concepts as applied to the whitefly Bemisia tabaci systematics: How many species are there? *Journal of Integrative Agriculture,11*, 176–186. https://doi.org/10.1016/S2095-3119(12)60002-1

McCutcheon, G. S., & Simmons, A. M. (2001). Relationship between temperature and rate of parasitism by Eretmocerus sp. (Hymenoptera: Aphelinidae), a parasitoid of Bemisia tabaci (Hornoptera: Aleyrodidae). *Journal of Agricultural and Urban Entomology,18*, 97–104.

Milenovic, M., Eickermann, M., Junk, J., & Rapisarda, C. (2023). Life history parameters of Bemisia tabaci MED (Hemiptera: Aleyrodidae) in the present and future climate of central Europe, predicted by physically realistic climatic chamber simulation. *Environmental Entomology*. https://doi.org/10.1093/ee/nvad023

Milenovic, M., Wosula, E. N., Rapisarda, C., & Legg, J. P. (2019). Impact of host plant species and Whitefly Species on feeding behavior of Bemisia tabaci. *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2019.00001

Nasruddin, A., & Mound, L. A. (2016). First record of *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae) severely damaging field grown potato crops in South Sulawesi, Indonesia. *Journal of Plant Protection Research, 56*(2), 199–202. https://doi.org/10.1515/jppr-2016-0023

Park, Y., Kim, S., Lee, S. H., & Lee, J. H. (2021). Insecticide resistance trait may contribute to genetic cluster change in Bemisia tabaci MED (Hemiptera: Aleyrodidae) as a potential driving force. *Pest Management Science,77*, 3581–3587. https://doi.org/10.1002/ps.6412

Plouvier, W. N., & Wajnberg, E. (2018). Improving the efficiency of augmentative biological control with arthropod natural enemies: A modeling approach. *Biological Control,125*, 121–130. https://doi.org/10.1016/j.biocontrol.2018.05.010

Powell, D., & Bellows, T., Jr. (1992). Adult longevity, fertility and population growth rates for Bemisia tabaci (Genn.) (Hom., Aleyrodidae) on two host plant species. *Journal of Applied Entomology,113*, 68–78. https://doi.org/10.1111/j.1439-0418.1992.tb00637.x

Qiu, B. L., De Barro, P. J., Xu, C. X., & Ren, S. X. (2006). Effect of temperature on the life history of Encarsia bimaculata (Hymenoptera: Aphelinidae), a parasitoid of Bemisia tabaci (Hemiptera: Aleyrodidae). *European Journal of Entomology,103*, 787–792. https://doi.org/10.14411/eje.2006.107

Qiu, Y. T., Van Lenteren, J. C., Drost, Y. C., & Posthuma-Doodeman, C. (2004). Life-history parameters of Encarsia formosa, Eretmocerus eremicus and E. mundus, aphelinid parasitoids of Bemisia argentifolii (Hemiptera: Aleyrodidae). *European Journal of Entomology,101*, 83–94. https://doi.org/10.14411/eje.2004.017

Ripamonti, M., Galetto, L., Maron, F., Marzachì, C., & Bosco, D. (2022). Scaphoideus titanus fitness on grapevine varieties with different susceptibility to Flavescence dorée phytoplasma. *Journal of Applied Entomology*. https://doi.org/10.1111/jen.13075

Rodríguez, E., Téllez, M. M., & Janssen, D. (2019). Whitefly control strategies against tomato leaf curl new delhi virus in greenhouse zucchini. *International Journal of Environmental Research and Public Health,16*, 2673. https://doi.org/10.3390/ijerph16152673

Semenov, M. A., & Stratonovitch, P. (2010). Use of multi-model ensembles from global climate models for assessment of climate change impacts. *Climatic Research,41*, 1–14. https://doi.org/10.3354/cr00836

Stansly, P. A., & Naranjo, S. E. (2010). *Bemisia: Bionomics and Management of a global pest*. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-2460-2

Tebaldi, C., & Knutti, R. (2007). The use of the multi-model ensemble in probabilistic climate projections. *Philosophical transactions of the royal society A: mathematical physical and engineering sciences,365*, 2053–2075. https://doi.org/10.1098/rsta.2007.2076

Therneau, T. (2022). A Package for Survival Analysis in R. R package version 3.3–1. https://CRAN.R-project.org/package=survival

Tylianakis, J. M., Didham, R. K., Bascompte, J., & Wardle, D. A. (2008). Global change and species interactions in terrestrial ecosystems. *Ecology Letters,11*, 1351–1363. https://doi.org/10.1111/j.1461-0248.2008.01250.x

Wang, R., Fang, Y., Mu, C., Qu, C., Li, F., Wang, Z., & Luo, C. (2018). Baseline susceptibility and cross-resistance of cycloxaprid, a novel cis-nitromethylene neonicotinoid insecticide, in Bemisia tabaci MED from China. *Crop Protect,110*, 283–287. https://doi.org/10.1016/j.cropro.2017.02.012

Xie, W., Yang, X., Chen, C., Yang, Z., Guo, L., Wang, D., Huang, J., Zhang, H., Wen, Y., Zhao, J., Wu, Q., Wang, S., Coates, B. S., Zhou, X., & Zhang, Y. (2018). The invasive MED/Q Bemisia tabaci genome: A tale of gene loss and gene gain. *Bmc Genomics,19*, 68. https://doi.org/10.1186/s12864-018-4448-9

Zandi-Sohani, N., & Shishehbor, P. (2011). Temperature effects on the development and fecundity of Encarsia acaudaleyrodis (Hymenoptera: Aphelinidae), a parasitoid of Bemisia tabaci (Homoptera: Aleyrodidae) on cucumber. *Biocontrol,56*, 257–263. https://doi.org/10.1007/s10526-010-9318-6

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