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RESEARCH

Factors driving thrips pressure across strawberry-growing regions in Switzerland

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Abstract
Thrips are important pests of everbearing strawberries worldwide. The emergence of resistance and the ban on several active ingredients mean that alternatives to insecticides need to be developed. Augmentative biological control in many cases has proved successful in controlling thrips; however, in certain cases it fails to keep thrips below the economic damage threshold. Identifying key factors influencing thrips populations is essential. We aimed to assess how thrips population dynamics varied by thrips species, grower practice and location of strawberry plots. In 2022 and 2023, a network of 43 plots in all the main strawberry-growing regions of Switzerland was established. Thrips were counted, adults identified to species level, and the management practices of the growers as well as the crops, topography and temperatures of the plots were recorded. The main species were *Frankliniella occidentalis* (68% of samples), *Thrips tabaci* (13%), *F. intonsa* (12%), and *T. fuscipennis* (5%) in varying proportions from one plot to another. Only the environmental factors altitude, temperature and distance from a meadow explained a sufficient proportion of thrips population variability. We also observed a link between the distance to the forest and the extent of damage done by thrips to strawberries. No differences were detected between the control strategies used suggesting that the use of insecticides or biocontrol agents is similarly effective. These results underscore the importance of considering the landscape and surrounding host plants in thrips management strategies.

Keywords *Fragaria* · *Thrips* · *Frankliniella* · Integrated pest management · Species diversity · Landscape

Key message

- The aim was to identify the key drivers of thrips populations in strawberries.
- Environmental factors explained more thrips population variability than management factors.
- Thrips numbers increased with lower distance from meadows, lower altitude, and lower temperature.
- The main species were *Frankliniella occidentalis*, *F. intonsa*, *Thrips tabaci* and *T. fuscipennis*.
- The most promising avenue for strategy improvement is other host plant management around crops.

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Introduction

Strawberries are the most widely produced and consumed berry in the world (FAO 2024). The taste and visual quality of the product are essential to guarantee sales that cover the relatively high production costs (Bhat et al. 2015; Melis et al. 2021). Pests are one of the main threats to strawberry quality and yield (Strzyzewski et al. 2021) and thrips constitute a key group of pests worldwide and in Switzerland (FUS, Agroscope, FiBL 2022; Lahiri et al. 2022). By feeding on plants, adults and larvae cause damage to flowers, fruits and leaves. Symptoms observed on flowers and fruits are mainly bronzing, grooves, cat faces, prominent seeds, reduced fruit size, and diminished fruit set (Koike et al. 2009; Strzyzewski et al. 2021).

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For many years, only insecticides have been used to combat this pest, but as the insect's life cycle is very short, insecticide resistance has developed (Bielza 2008; IRAC 2016). Furthermore, fewer insecticides are registered for use against thrips, due to concerns for human health and environmental impact (BLV 2024). Today, many biological control agents (BCAs) are available for augmentative releases in strawberry greenhouses against thrips, including phytoseiid and anthocorid generalist predators (Vervoort et al. 2017; Mouratidis et al. 2023a; Alonso et al. 2024). Conservation biological control practices have also gained momentum, incorporating ecological infrastructures, such as flower strips, to promote the establishment of spontaneously occurring BCAs (Busuulwa et al. 2024). However, BCAs sometimes do not give sufficient results, particularly if pest attack occurs outside their activity period or if the thrips population is too large (Lahiri et al. 2022). In Switzerland, certain growers experience that BCA populations are insufficient to keep thrips populations below the economic damage threshold, despite using the same BCA release practices (Producers at sector meetings, personal communication, 2022). This high unexplained heterogeneity between thrips populations in plots subjected to the same practices has also been observed in numerous studies around the world (eg. Cluever et al. 2016; van Kruistum and Belder 2016; Panthi et al. 2024), highlighting that certain parameters are not well taken into account in control strategies.

The factors influencing thrips populations in strawberry crops require further investigation. Abiotic conditions such as temperature, humidity, and light impact thrips populations under controlled conditions (Steiner et al. 2011; Ullah and Lim 2015; Garrick et al. 2016; Tokaji and Shiro 2020; Fountain et al. 2022; Montemayor et al. 2022). In Switzerland, high altitude crops seem more susceptible to thrips attack (Linder et al. 1998). Also, alternative host plants near strawberry crops may promote thrips population growth (Sutter et al. 2022; Canovas et al. 2023a). Management practices such as variety (Abdelmaksoud et al. 2020; Mouden et al. 2021), type of crop system, and soil cover (van Kruistum and Belder 2016) are also likely to impact thrips populations in controlled systems. In other crops, planting density (Khaliq et al. 2016; Krob et al. 2022), planting date (Kerns et al. 2019) and crop rotation (Buckland et al. 2013) have been shown to affect thrips populations. There may also be potential interactions between the different control measures (Stara et al. 2011; Biondi et al. 2012) and the distinct thrips species occurring in the crop (Bhuyain and Lim 2020; Gao et al. 2021). However, thrips are minute insects and distinguishing between species is difficult, especially at the larval stage (Atakan et al. 2016; van Kruistum and Belder 2016), so thrips are sometimes considered as a single group without distinction of species or even genus. This happens regularly in practice, in the field for growers, and sometimes even in scientific studies (e.g. Melis et al. 2021; Coates et al. 2023). The most damaging thrips species to strawberries in continental Europe are the invasive *Frankliniella occidentalis* Pergande, originally from the western USA (Kirk and Terry 2003), and to a lesser extent *Frankliniella intonsa* Trybom and *Thrips tabaci* Lindeman (Lahiri et al. 2022).

The latest published species inventories in Swiss strawberry crops revealed that the most prevalent species were *Thrips fuscipennis* Haliday, *T. tabaci*, and *F. intonsa* (Linder et al. 1998; Höhn et al. 1999). *F. occidentalis* was also present in large numbers, but only in certain plots in eastern Switzerland (Höhn et al. 1999). In 2021, another survey conducted in Valais, southwest Switzerland, found that *F. occidentalis* was predominant (Agroscope, unpublished data). The disparity in the proportions of each species in each plot varied greatly, with one species often being predominant. These studies found that crops of everbearing varieties were the most susceptible to thrips attack, probably because pollen is regularly available from April to September. Everbearing varieties were also those with the highest proportion of *F. occidentalis* (Linder et al. 1998; Höhn et al. 1999).

More research is needed on both thrips species and parameters that can explain residual variability in thrips populations in Switzerland. Crop management techniques to improve thrips control can then be identified. We collaborated with strawberry producers and regional advisors, to identify the main factors influencing thrips populations in Swiss strawberries. Our objectives were: (i) to provide an updated overview of the thrips species present in Swiss strawberry agro-ecosystems, (ii) to identify which management and environmental factors influence thrips populations and damage as well as their relative importance, and (iii) to determine whether the results vary depending on the pest thrips species.

Material and methods

Study sites

The plots sampled were spread across all the strawberry-growing regions of Switzerland, in the cantons of Bern, Geneva, Lucerne, St. Gallen, Thurgau, Ticino, Valais, Vaud, and Zurich (Fig. 1). Where possible, samples were taken in two consecutive years but some plots, in particular those without strawberry crops for 2 consecutive years, were only monitored for 1 year. Overall, 43 different plots were sampled, 31 in 2022 and 33 in 2023. Only plots of everbearing strawberries and a homogeneous cultivation surface were selected, i.e. a single infrastructure (tunnel, greenhouse or field) and a single variety. An exception was made for plots with more than 3 everbearing varieties, as these plots are representative of a certain cultivation

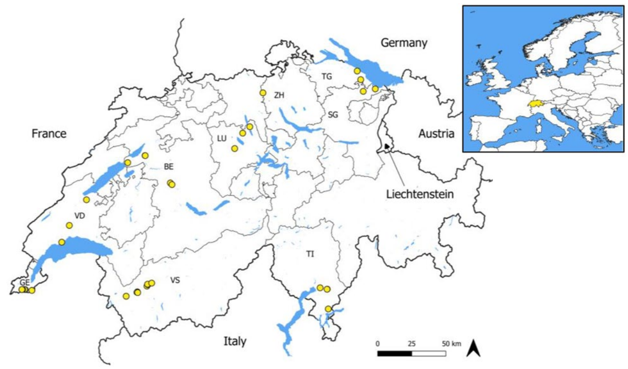

Fig. 1 Location of the sampled plots (yellow dots) on the map of Switzerland. In the cantons of Geneva (GE), Valais (VS) and Bern (BE), some sites being very close to each other are merged on the map. The other cantons are Lucerne (LU), St. Gallen (SG), Thurgau (TG), Ticino (TI), Vaud (VD), and Zurich (ZH)(n = 43)

method found in Switzerland, particularly on farms selling directly to consumers. The plots were selected by canvassing and voluntary registration by growers.

Thrips populations monitoring

On each plot, a sample of 50 flowers was taken following a cross-sampling pattern consisting of the 2 diagonals of each plot, with 25 flowers sampled per diagonal. The flowers in the sample were cut directly above a 50 cl plastic jar of 70% alcohol. This sampling took place as soon as flowering in the plot was complete and homogeneous (90% of flowering stems having fully open flowers). It was repeated at each flowering cycle until the third. A complete flowering-fruiting cycle lasts around 2 months. The periodicity of these cycles depends on the region: the earliest plots have their first cycles in the second half of March and the latest at the end of May. The insects present in the flowers were then counted under a stereo microscope in the laboratory after rinsing the flowers with alcohol and filtering the resulting mixture through a 0.45 µm mesh cellulose nitrate filter. Thrips were categorised into two developmental stages: adult and immature. *Aeolothrips* spp., a genus of spontaneously occurring facultative predatory thrips, were also counted at this stage. In 2022, the proportion of each main species was estimated and a subsample of adults identified; in 2023, all adults were identified. Identification to species level was performed through a stereo microscope using dichotomic keys available for the European fauna (Mound et al. 1976; zur Strassen 2003). When necessary, specimens were mounted on microscopic slides using Hoyer's medium or Canada Balsam, for detailed examination using a phase contrast microscope.

Fruit damage assessment

In 2023, 2 weeks after the second sampling, fruit damage was assessed. The percentage of surface area with thrips damage was measured on 50 fruits per plot (2 diagonals of 25). The intensity of the damage was also recorded and categorised into 3 categories: i) discolouration due to thrips feeding, clear circles around achenes or localised; ii) discolouration damage covering the surface more evenly, presence of prominent achenes; or iii) discolouration damage with a dried-out effect, the fruit is no longer shiny, possibly with cracks (Online Resource 1). The assessment was carried out by the same person in all plots and only the primary fruits of inflorescences were assessed. Other non-thrips damage observed was not taken into account to obtain a result entirely attributable to thrips. The fruit was then classified as unmarketable according to the following thresholds: 40% of the surface in category i, 20% in category ii and 5% in category iii. At the same time, the abundance of fruit and flowers in the plot was estimated from three measurements: the number of flowering stems on 25 plants in the plot, the number of flowers and fruit on one stem per plant and the planting density. We saw no trend between the amount of damage and fruiting density, suggesting that there was no risk of bias associated with this parameter of heterogeneity between plots.

Retrieving cultivation management data

Questionnaires were sent out to growers to gather information on cultivation practices. The information requested was: control schedules, i.e. treatments used and BCAs introduced, as well as dates and doses, planting densities, varieties, type of substrate, type of plant, and the number of consecutive years strawberries had been grown on the plot. The type of soil cover and infrastructure were recorded during visits. Table 1 summarizes the management methods used. All the varieties present on fewer than 5 plots were grouped in a single category "other" to increase the power of the model. As the treatment protocols had many variations and the number of observations did not allow categorical variables with more than 6 variations to be treated, the active control methods were considered as binomial (presence/absence) for the insecticide and BCA categories. Details of the products and BCAs used per plot are available in Online Resource 2. The insecticides used were: abamectin, spinosad, azadirachtin A, acetamiprid, spirotetramat, pyrethrins and a physical insecticide based on the 3D-IPNS technology. The BCAs used were *Beauveria bassiana* Vuill., *Orius laevigatus* Fieber, *Neoseiulus cucumeris* Oudemans, *Amblyseius swirskii* Athias-Henriot and *Neoseiulus californicus* McGregor.

Table 1 Description of parameters classified as a) management (n = 60) and b) environmental (n = 60)

a)	mean	min	1st Qu.[a]	median	3rd Qu	max
Plot size (m^2)	6799.0	103.0	1795.0	4030.0	6074.0	40,971.0
Planting density (plant/m)	8.0	4.0	6.0	8.0	7.2	12.0
No. consecutive years of strawberry cultivation	15.3	1.0	4.8	9.0	11.4	31.0
	categories					
Year	2022 (n = 27), 2023 (n = 33)					
Soil cover	plastic (n = 29), grass (n = 18), uncovered soil (n = 13)					
Infrastructure type	tunnel (n = 28), greenhouse (n = 18), high tunnel (n = 12), open field = (n = 2)					
Medium	substrate (n = 51), soil (n = 9)					
Plant type	fridge (n = 5), minitray (n = 24), clods (n = 4), tray (n = 27)					
Biocontrol agents (BCA)	introduced (n = 37), not introduced (n = 23)					
Insecticides	used (n = 27), not used (n = 31), unknown (n = 2)					
Interaction BCA*insecticides	neither used (14), both used (18)					
Variety	Favori (n = 10), Mara des Bois (n = 22), Murano (n = 6), Vivara (n = 13), others (n = 9)					
b)	mean	min	1st Qu.[a]	median	3rd Qu	max
Latitude (deg)	46.2	46.0	46.2	46.5	47.0	47.6
Longitude (deg)	7.2	6.1	6.4	7.4	8.3	9.5
Altitude masl	442.0	199.0	410.8	455.9	471.5	802.0
Precocity index	172.1	110.0	158.7	171.0	184.7	236.3
Distance to the forest (m)	343.2	13.9	252.5	372.0	506.4	763.0
Distance to the meadow (m)	249.6	39.5	164.0	283.5	400.0	886.3
Mean temperature (°C)	15.4	13.6	14.5	15.3	16.1	17.5
	categories					
Year	2022 (n = 27), 2023 (n = 33)					
Infrastructure type	tunnel (n = 28), greenhouse (n = 18), high tunnel (n = 12), open field = (n = 2)					
Region	BE + VD (n = 11), GE (n = 15), LU + ZH (n = 4), SG + TG (n = 8), TI (n = 6), VS (n = 16)					

[a.]quartile

Retrieving environmental data

Using QGIS (QGIS Development Team) the size of the plots and their location (altitude, latitude, longitude and region) were calculated (meters above sea level and decimal degrees WGS 84). The distances between the plots and the nearest forest and meadow were also obtained. The measurements were taken from the centre of the plots. The information relating to forests was retrieved from the swissTLM3D database (Swisstopo 2024) and that related to meadow from the layers of areas for the promotion of biodiversity categories I and II. Average temperatures from March to July were obtained from the weather stations closest to the plots (Agroscope 2024). The sampling dates were converted to Julian days and averaged to compute a precocity index. Table 1 summarizes the environmental parameters observed.

Data analysis

The results were analysed using R software version 4.2.2 (R Core Team 2022), with figures generated using ggplot2 (Wickham 2016) and QGIS (QGIS Development Team). Some flowering cycles were missing in certain years (due to agronomic practices or commercial reasons). To enable comparisons between plots, the missing datapoints were estimated using data from the 2 observed flowering cycles and a linear model derived from all the other data. Four plots for which 2 flowering cycles were missing were excluded from the analysis. For 2 plots, the management interventions were not known and thus those plots had to be excluded from the management model.

First, the relationships between the variables (both response and explanatory) were examined using Pearson, Spearman, tetrachordic, and Cramer's V relation coefficients, depending on the variable type and distribution. The dissimilarity in thrips species composition between plots was assessed using the Bray–Curtis Dissimilarity indicator. Every time 2 explanatory variables were strongly correlated (corr. coeff. > 0.7, or > 0.5 for Cramer's V) only one was selected. The correlation between latitude and mean temperature was high (Pearson r: −0.74, $p < 0.001$). It was considered that temperature was the most relevant parameter, and latitude was therefore excluded from the models. The correlation between the type of medium (soil or substrate) and the crop protection practices (use of BCAs or insecticides) was high (R2 −0.85 and −0.62 respectively), because no BCAs were released in uncovered soil plots, and only one of these plots was treated with insecticides. Furthermore, cultivation medium had a strong relationship with the plant type used (Cramer's V = 0.56), and the infrastructure type (Cramer's V = 0.51), and was thus excluded from the models. None of the other variables included in the models had correlations. We also excluded categorical variables with too low diversity (only one category observed or less than 5 observations in the second category). We ran 2 types of models. The first was run to select from among the environmental variables that best described the response variables. This model included all the environmental data (see above) plus the total population of *Aeolothrips* spp. observed per plot, the type of infrastructure and the sampling year. The second model was run to select from among the management variables including the sampling year and all the management data (see above) and included an interaction effect between the use of insecticides and the use of BCAs. This interaction factor was the only one to be included in the analysis because of the limitations in statistical power resulting from the limited number of observations. However, the year and type of infrastructure were included in both models due to the strong possibility of interdependence with other parameters. We used the second-order Akaike Information Criterion AICc (Hurvich and Tsai 1989) through the dredge function (Bartoń 2024) to select the most parsimonious model among the models explaining the response variables. Quasi-binomial models were used to model the proportion of non-marketable fruit, linear models with log + 1 transformation were used to model the impact of management on the population and negative binomial models were used to model the impact of environmental data on population (as the homoscedasticity assumption was not met). Those models were compared to the null model using F-tests (linear and quasi-binomial) and Likelihood ratio (LR) tests (negative binomial). We checked for the presence of multicollinearity using the variance inflation factor (vif). A sensitivity analysis was carried out to assess the viability of the results for the best model selected. This analysis involved reproducing the models on only part of the dataset (each year separately and the dataset without "atypical" values, defined as those exceeding the thresholds of 14 thrips per flower and 60% of unmarketable fruit). The general spatial autocorrelation of each quantitative parameter was assessed using the Moran's I tests. Multiple joint-count tests (corrected using the Bonferroni method) were used for categorical variables. For quantitative variables with significant global spatial autocorrelation and the main response variables, the Moran's LISA (local indicators of spatial association) test was used to detect local trends. The response variables evaluated were the total thrips population observed on the plot during the year, the proportion of unmarketable fruit due to thrips damage, and the thrips population observed on the plot during the year 2023 for each main species.

Results

Thrips populations

Thrips were observed in all plots. Most population peaks occurred during the second and third flowering cycles, more rarely during the first (Fig. 2). The main species was *F occidentalis* (67% of all thrips sampled), followed by *F. intonsa* (13%), *T. tabaci* (13%) and *T. fuscipennis* (5%). The rest of the population was made up of facultative predatory species (*Aeolothrips intermedius* Bagnall and *Haplothrips kurdjumovi* Karny), and other flower thrips species (*Haplothrips leucanthemi* Schrank, *Thrips atratus* Haliday, *T. pillichi* Priesner, *T. flavus* Schrank, *T. major* Uzel, and *T. minutissimus* L.) and a few species of thrips normally found in grasses (*Anaphothrips obscurus* Muller, *Aptinothrips rufus* Haliday, and *Limothrips cerealium* Haliday). Except for *A. intermedius*, only one or two individuals of these other species were observed in total. The similarity between plots was high when these were located less than 300 m apart (Bray–Curtis dissimilarity < 0.2) and intermediate up to 1000 m of distance between plots (Fig. 3).

The species were not evenly distributed throughout Switzerland and the *F. occidentalis* population was highest in the cantons of Geneva, Valais, Ticino, St Gallen and Thurgau. *Haplothrips* spp. were only observed in Ticino. *Thrips tabaci* and *F. intonsa* were the majority in the central plateau (Fig. 4). Populations of *F. intonsa*, although similar in total numbers to *T. tabaci*, had a restricted distribution and occurred in larger groups; 30% of plots exceeding the threshold of 3 thrips per flower, which

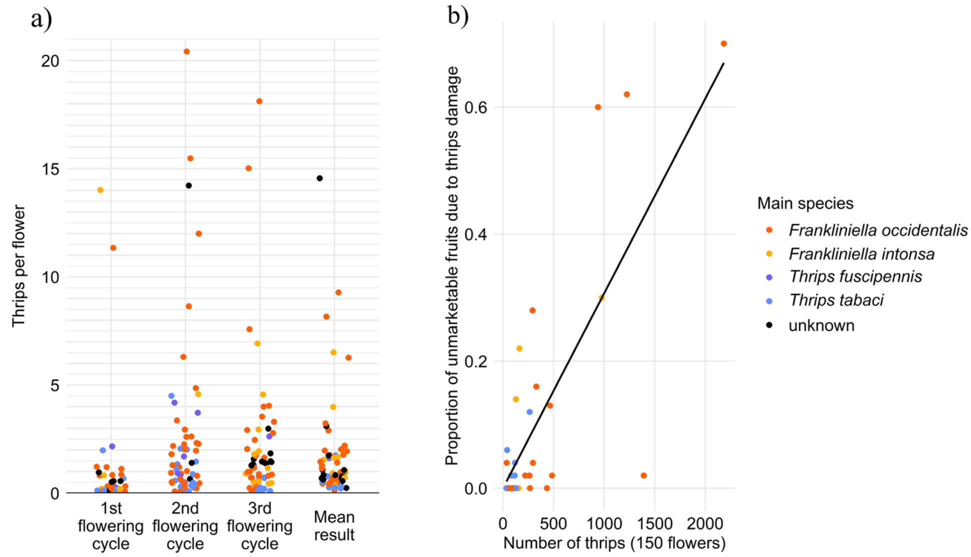

Fig. 2 (**a**) Distribution of thrips populations observed with the dominant species during the years 2022 and 2023 (n = 60), and (**b**) relationship to the proportion of unmarketable fruit in the plot with the dominant species in the plot during the year 2023 (n = 27). All data that are at least partially based on imputation are noted as "unknown" main species

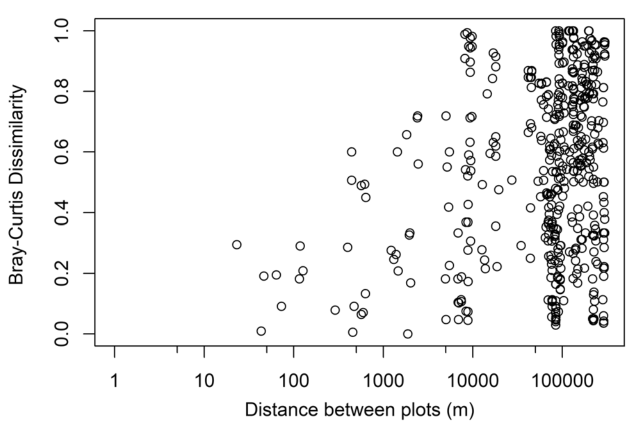

Fig. 3 Difference between observed species proportions (Bray–Curtis Dissimilarity) depending on the distance between two plots

typically leads to economic damage, had *F. intonsa* as the dominant species compared to 7% for *T. tabaci*. The populations of *T. tabaci* and *F. intonsa* were significantly spatially autocorrelated (Moran's I = 0.12, 0.06/p = 0.007, 0.006), as was the proportion of *T. fuscipennis*, albeit to a lesser extent (Moran's I = 0.02/p = 0.003). The proportion of non-marketable fruit was spatially autocorrelated overall (Moran's I = 0.18/p = 0.006). The other response variables did not show significant overall spatial autocorrelation, but local LISA analysis revealed trends of lower thrips populations in the regions of Bern, Vaud and Lower-Valais (West Valais). These tests also identified regions with less damage to fruit: Bern, Vaud and Valais, and those with more damage: Geneva, St. Gallen and Thurgau.

Effect of environmental factors on thrips' population and damage

The best model identified to describe the total thrips population with environmental variables included altitude, distance to the nearest meadow, mean temperature, and year (Table 2, Online Resource 3). The thrips population decreased with increasing altitude (− 0.55% per m), increasing distance from meadows (− 0.15% per m) and increasing temperature (− 32% per °C) and there were more thrips detected in 2023 (+ 65%, Fig. 5). This model explained around 30% of the variability (null deviance 96.181 on 59 df, residual deviance 66.016 on 55 df) and had a difference in AICc (dAICc) of 15.901 with the null model (null AICc = 794.185, full AICc = 778.284). The predictors included in the model significantly improve fit compared with the null model described (LR statistic = 25.28, df = 4, p < 0.001). No multicollinearity was detected (all vif < 3). The parameters longitude, total number of *A. intermedius*, distance to the forest, precocity index, type of infrastructure, mean temperature and region did not improve the model obtained. However, the parameters total number of *A. intermedius* and distance to forest were present in models with a dAICc < 2 compared with the best model (Online Resource 4). All the sensitivity analyses showed stable trends, but the significance of the observed impact of temperature and year was dependent on the values above 700 thrips per plot (4.66 thrips per flower, Online Resource 5). Replacing the total thrips population variable with the *F. occidentalis* or *F. intonsa* population did not change the model trends, and the impact of the parameters remained individually significant, except in the case of "distance to meadow", which was no longer significant for either species. The model did not describe the *T. tabaci* population; the impact of altitude on this species was the

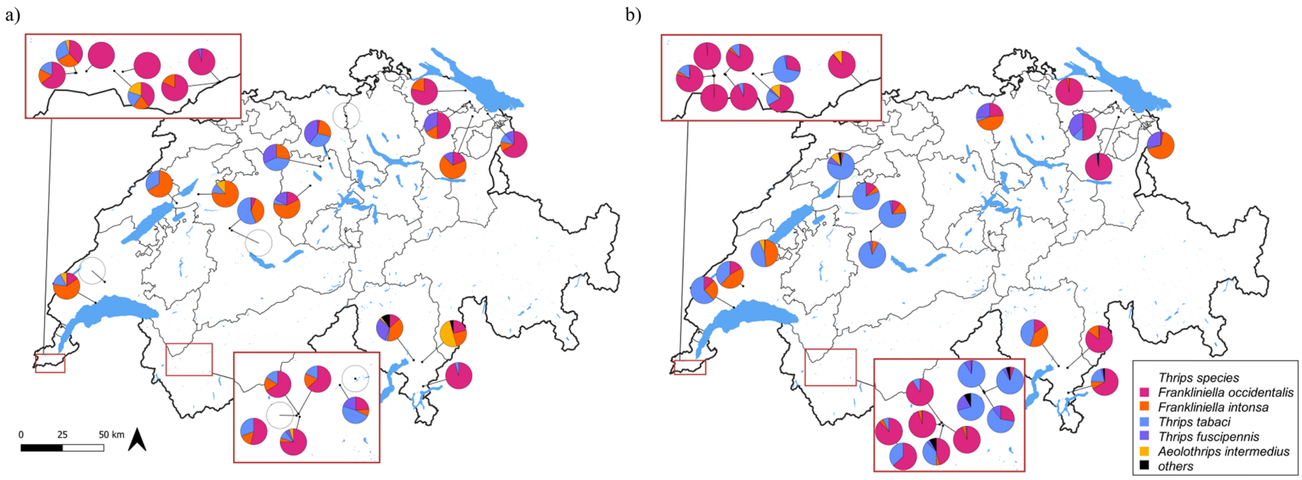

Fig. 4 Main species observed on plots of everbearing strawberries in Switzerland in (**a**) 2022 and (**b**) 2023. Sum of three samplings of 50 flowers during the three flowering cycles. The empty circles represent plots without available data. The size of the circles represents the size of the population. A minimum size has been imposed on the small diagrams to make them easier to read (n = 60)

Table 2 Effect of environmental variables on (a) the total thrips population in Swiss everbearing strawberry crops (three samples of 50 flowers sampled at each flowering cycle) (n = 60), (b) the percentage of unmarketable fruit due to thrips damage (n = 33)

(a)						
Model/response variable	Explanatory variables	Model parameters				
GLM with a negative binomial distribution/thrips population (3 × 50 flowers)	Model constant	Estimates	IRR[a]	SE[2]	*z*	*p*
	Year (2023)	14.0547		3.2735	4.29	<0.001
	Altitude (m)	0.5035	0.6545	0.2438	2.07	0.0389
	Distance to meadow (m)	−0.0055	−0.0055	0.0014	−4.04	<0.001
	Temperature (°C)	−0.0015	−0.0015	0.0006	−2.30	0.0217
		−0.3888	−0.3221	0.1732	−2.24	0.0248

(b)					
Model/response variable	Explanatory variables	Model parameters			
GLM with a quasi-binomial distribution/proportion of unmarketable fruit	Model constant	Estimates	SE[b]	*t*	p
	Distance to forest (m)	−2.3290	0.4778	−4.88	<0.001
	Thrips population (3 × 50 flowers)	−0.0032	0.0014	−2.26	0.0315
		0.0025	0.0005	5.47	<0.001

[a]Incidence Rate Ratio, [b]Standard Error

opposite. Separating model selection for thrips population variations by year showed differences between 2022 and 2023. For 2022, the best environmental predictors were altitude and distance to meadow. For 2023, the best predictors were region, the distance to the forest, and distance to meadow (Online Resources 4, 6).

The best model identified to describe the proportion of unmarketable fruits (min 0; Q1 0; median 0.02; mean 0.11; Q3 0.13; max 0.7) due to thrips damage with environmental variables included the total population of thrips observed, and the distance to the forest (Table 2). The proportion of unmarketable fruits increased with increasing thrips population (+0.25% per thrips in 150 flowers) but decreased with increasing distance to the forest (−0.32% per m, Fig. 6). This model explained around 60% of the variability (null deviance 9.314 on 32 df, residual deviance 3.747 on 30 df). The predictors included in the model significantly improve the fit compared with the null model described ($F = 20.459$, $df = 2$, $p < 0.001$,); the addition of the parameter "distance to nearest forest" significantly improved the model compared to the one including only the thrips population ($F = 5.535$, $df = 1$, $p = 0.025$). No multicollinearity was detected ($vif = 1.3$). The parameters altitude, mean temperature, longitude, total number of *A. intermedius*, distance to the nearest meadow, precocity index, type of infrastructure, region and mean temperature did not improve the model obtained. The sensitivity analysis

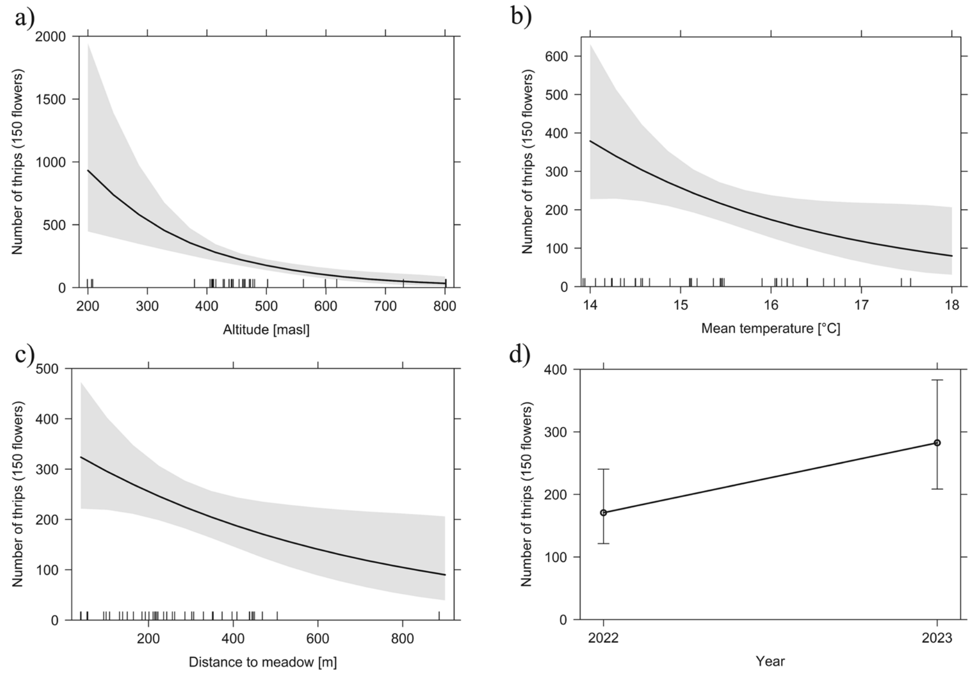

Fig. 5 Multiple regression of the relationship between (**a**) altitude, (**b**) mean temperature, (**c**) distance to the nearest meadow and (**d**) year of sampling and the total thrips population observed in plots of everbearing strawberries in the years 2022 and 2023 during three samplings of 50 flowers (one per flowering cycle). Regression calculated using a generalized linear model with a negative binomial distribution

showed stable trends, but for both parameters included in the model, the significance of the results was dependent on the values above 60% of unmarketable fruits (Online Resource 5). Adding the proportion of one of the main species to the simple model including only the thrips population did not have a significant impact on the model. There was significant positive spatial autocorrelation for altitude (north Switzerland = high except for plots on the shores of Lake Constance; south Switzerland = low except for central Valais, I = 0.24, $p = 0.002$), average temperature (north = cold, south = warm; I = 0.61, $p < 0.001$), precocity (Geneva and Ticino = early; Valais and central Switzerland = late, I = 0.39, $p < 0.001$), a slight positive autocorrelation for distance to meadow (western Valais = high; Geneva and Lucerne = low, I = 0.12, $p = 0.048$) and, with the 2022 plots, a positive autocorrelation of infrastructure type “greenhouses” (over-representation in Geneva, Thurgau and St. Gallen; Join-count = 3.1 [expected = 1.4], $p < 0.001$). No other environmental variables showed autocorrelation.

Management factors affecting thrips’ population and damage

Only two models with management variables outperformed the null model to describe total thrips population variation: one with the parameters year and insecticide and the other with the parameter variety (Online Resources 3, 4). But none of them was significant. The first model showed signs of a positive relationship with the use of insecticide and the year 2023 compared to 2022 ($p = 0.1$ and 0.08 respectively). But the model with those two parameters was not significant (dAICc = 0.56, F = 2.527, $p = 0.09$). In the second model, the variety Mara des Bois showed a higher thrips population than the varieties Vivara and Favori ($p = 0.03$). But the model with the parameter variety was only marginally significant (dAIC = 0.23, F = 2.402, $p = 0.06$). The parameters plot size, planting density (plant/m), no. consecutive years of strawberries, soil cover, infrastructure type, young plant type, and BCAs did not improve the null model. Separating model selection for thrips population variations by year showed differences between 2022 and 2023. The best management predictors for 2022 were the use of biocontrol and the variety. For 2023, no management predictor improved the null model (Online Resources 4, 6).

The best model identified to describe the proportion of unmarketable fruits due to thrips damage with management variables included the total population of thrips observed, and the soil cover (Table 3, Fig. 6c). The proportion of unmarketable fruits increased with increasing thrips population but was lower for plots with uncovered soil compared to those with plastic cover, or with grass. This model explained approximately 72% of the variability (null deviance 7.243 on 31 df, residual deviance 2.099 on 28 df). The predictors included in the model significantly improved the fit compared with the null model described (F = 20.807, df = 3, $p < 0.001$). Adding the parameter soil cover significantly improved the model compared to the one including only the thrips population (F = 14.046, df = 2, $p < 0.001$). No multicollinearity was detected (vif < 1.3).

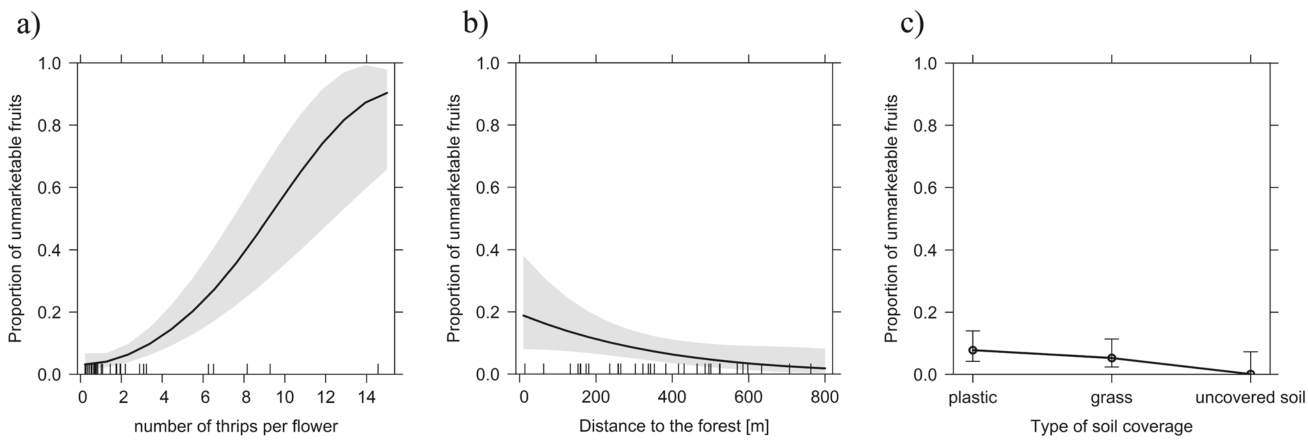

Fig. 6 Multiple regressions of the relationship between the proportion of unmarketable fruits observed in plots of everbearing strawberries and (**a**) the number of thrips during three samplings of 50 flowers (one per flowering cycle) and (**b**) the distance to the closest forest (m) and the same number of thrips and (**c**) the type of soil coverage. Regressions calculated using generalized linear models with quasi-binomial distribution

Table 3 Effect of management variables on the proportion of unmarketable fruit due to thrips damage. Best model identified including the thrips population (n = 32)

Model/response variable	Explanatory variables	Model parameters			
		Estimates	SE[1]	*t*	*p*
GLM with a quasi-binomial distribution/proportion of unmarketable fruit	Model constant (plastic covered)	−3.241	0.4099	−7.91	<0.001
	trips population (3 × 50 flowers)	0.003	0.0005	5.81	<0.001
	Soil coverage (grass)	−0.394	0.5178	−0.76	0.453
	Soil coverage (uncovered)	−5.114	2.0878	−2.45	0.021

[1]Standard Error

The parameters plot size, planting density (plant/m), number of consecutive years of strawberries, variety, insecticides, infrastructure type, young plant type, and BCAs did not improve the model obtained. The sensitivity analysis showed stable trends, and the significance of the results also stayed stable (Online Resources 5). In addition to the spatial autocorrelation observed for greenhouses (described in the previous subsection), positive spatial autocorrelation was observed for the strawberry varieties "Mara-des-bois" (over-representation in Geneva and Ticino, Join-count = 2.6 [expected = 1.4], $p = 0.012$), "Murano" (over-representation in Bern and Lucerne, Join-count = 0.6 [expected = 0.1], $p = 0.002$), and "Vivara" (over-representation in Valais in 2023, Join-count = 0.8 [expected = 0.18], $p = 0.002$), for the type of land cover "grass" (over-representation in Valais, Join-count = 1.8 [expected = 0.8], $p = 0.005$) and for the use of biocontrol (under-representation in Ticino and central Valais in 2023, Join-count = 3.4 [expected = 1.2], $p = 0.002$). No other management variables showed autocorrelation.

Discussion

Thrips species distribution

To our knowledge, this study is the first monitoring of thrips species in everbearing strawberry crops at a national level in Switzerland. As expected, *F. occidentalis* has clearly become the most problematic species, with increasing importance in the crop since the last published surveys (Linder et al. 1998; Höhn et al. 1999). These results confirm practitioners' observations and indicate that the increase in thrips-related problems is probably linked to the spread of this species. However, other species such as *T. fuscipennis*, *T. tabaci* and *F. intonsa* also showed impacts on yields in at least one plot. Thrips attacks occurred mainly in midseason, with further significant impacts at the end of the season, and only rarely at the beginning of the season, highlighting the importance of thrips in everbearing strawberries which grow over longer periods. These results are similar to those observed in the past in Switzerland (Linder et al. 1998; Höhn et al. 1999; Koller et al. 2024) and elsewhere in Europe (Tuovinen and

Lindqvist 2014; Nielsen et al. 2021). The distribution of species is in line with the state of knowledge: the regions of Geneva, Valais, Thurgau and Ticino have a climate favorable to the development of *F. occidentalis* and had historically a higher acreage of fruit, horticultural and vegetable crops, as well as much agricultural infrastructure (tunnels, greenhouses), which again favored the introduction of *F. occidentalis* and its spread (Reitz et al. 2020). In Central Switzerland, on the other hand, most crops are grown in open fields, and other crops are often favored. Also *T. tabaci* was present in the central region of Switzerland where, historically, a large part of Swiss tobacco production was concentrated (Alber and Gernot 1998). This predominance of *T. tabaci* in plots where *F. occidentalis* is less abundant is perhaps due to the absence of intense competitive interactions between the two species, which typically would favor the latter (Wu et al. 2021).

The importance of landscape context influencing thrips populations

The variability in thrips population between plots can be best explained by ecological factors, including altitude, mean temperature, yearly fluctuations and proximity to meadow. The year variable contained some variability linked to the adaptation of the protocol between the 2 years of monitoring, but it also illustrates very well the population differences that can be observed from one year to the next. Because of its inclusion in the model, it limits the detectability and importance of the mean temperature variable, but it probably includes some climatic parameters that could not be included otherwise, such as the general earliness of the season or humidity. The differences observed from one year to the next could be a clue as to which parameters were most important in years with low thrips pressure, such as 2022, and those with larger populations, such as 2023. However, to understand better the dynamics of thrips populations and the factors influencing them across varying pressure years, a longitudinal study with multiple high and low population years would be needed, allowing for more robust comparisons and more reliable recommendations. The altitude variable is a good illustration of the impact of a parameter on the landscape on an inter-regional scale. Contrary to what was observed by Linder et al. (1998), the thrips population decreased with altitude, and this difference in results is probably due to the geographical areas covered. Linder et al. (1998) included only one high-altitude plot in their study, located at an altitude of 1,000 m in western Valais, a plot which was not comparable (in terms of climate and altitude) to any of the areas included in our study. The negative relationship observed with temperature is unexpected. Thrips populations are often positively correlated with this parameter (Ullah and Lim 2015). This negative relationship could be explained through the integration of the altitude effect, which can override the influence of temperature on an inter-regional scale. On an intra-regional scale, lower temperatures– often associated with higher altitudes– are also correlated with lower natural BCAs activity (Zilahi-Balogh et al. 2007; Ren et al. 2022) and lower development of other host plants in the vicinity of the crops (Ameena et al. 2024). However, the chosen methodology for collecting temperature data (average temperature across the season from weather stations) is a limitation that warrants caution in interpreting the results, as under protected cultivation, microclimate may differ substantially from ambient conditions. The impact of parameters such as distance to the meadow, altitude, and mean temperature, all of which show spatial autocorrelation, combined with the absence of a measurable regional effect, suggests that these factors operate mainly at the intra-regional rather than inter-regional level, or that the models failed to capture regional effects adequately. The first hypothesis was supported by the best model selected for 2023, which includes both region and distance to the meadow as predictors. For the other parameters, the analysis may have been limited by 3 factors: (1) an imbalance in the number of plots across regions, (2) the high number of categories in the region variable, which was penalized in the model selection methods chosen, and (3) the choice of political divisions, which, while relevant in some cases, may not be optimal. For instance, the canton of Valais often showed clear differences between its western and central parts.

The effect of distance from meadows is the one that promises the greatest potential for integration into management strategies. Our study shows that on the scale of Swiss everbearing strawberries, it is one of the parameters that explains the most variability and therefore one of the greatest potentials for change. This positive impact of meadows or other host plants close to the plot on thrips populations in the plots has already been documented several times in strawberry crops, including in Canada (Canovas et al. 2023a, b), the USA (Kaur et al. 2024), and Switzerland (Koller et al. 2024). This effect is particularly important in cropping systems where the plots are small and therefore where this border effect affects a large part of the surface area. It has been described in nectarine orchards in Canada (Pearsall and Myers 2001), tomato, potato and onion crops in Brazil (Fernandes and Fernandes 2015), and in cotton-producing regions in Australia (Silva et al. 2018). Flights of thrips from the annual flowering plants into the greenhouse are known to occur (Jenser 1973). This type of migration is more likely to occur for endemic species that thrive in natural habitats within their geographical regions of origin, such as *T. tabaci*, *T. fuscipennis*, and *F. intonsa*. In contrast, such movements may be less important for the exotic *F. occidentalis*, which occurs in lower abundance than endemic species in the vegetation surrounding greenhouses in countries with similar thrips fauna and climatic conditions to Switzerland, such as the Netherlands (Vierbergen 2001; Mouratidis et al. 2023b). Further research would be needed to identify the thrips fauna associated with meadows surrounding Swiss strawberry crops, and to determine whether these thrips actively migrate into the crops.

The impact of distance from a forest, also a landscape parameter on an intra-regional scale, similarly illustrates the importance of local flora and surrounding landscape structure, parameters that have already been studied as correlating with thrips populations (Goethe et al. 2022; Doehler et al. 2023). Certain plants may promote pest populations by providing food and shelter, whereas others support BCAs, or influence both trophic levels (Parolin et al. 2012a, b). Species that flower during strawberry fruiting can provide alternative food sources, potentially reducing crop damage. In contrast, species flowering just before strawberry fruiting (or mown at fruiting time) may increase damage on nearby strawberry crops, as thrips are sufficiently mobile and may move short distances during the season (Panthi et al. 2021, Buitenhuis 2007). This phenomenon may explain why certain factors, correlated with a certain flora, influence thrips populations without having any impact on fruit damage, and vice versa, explaining variability in both thrips populations and in thrips-related damage on strawberries. Further research is needed to confirm these hypotheses. Investigating the role and management of host plants near strawberry fields, e.g. rational mowing, extending of control practices to surrounding vegetation or intercropping, may improve thrips management in everbearing strawberries (Messelink et al. 2021).

Absence of consistent management effects

Models including management parameters did not explain the variability within thrips populations well. This can be explained by the presence of multicollinearity, which reduced the models' detection capacity, and by the variability of the practices implemented by the growers. The number of observations was too small to detect robust significant effects, but trends were detected. The lack of detectable effect of insecticides can simply be explained by the inter-causal relationship between the thrips population and the use of insecticides. This trend also exists with the use of BCAs, but as these are introduced as a preventive measure, the effect is less pronounced. The results do not show a difference in impact between the all-BCA, all-insecticide and combined strategies. This suggests that the methods have similar effect scales in practice and correspond with what is often seen now (Sampson and Kirk 2016; Vervoort et al. 2017). A systematic literature review and meta-analysis also observed equivalent results between these two categories of control strategies: insecticides and BCAs (Schneeberger et al. 2025). However, these results should be interpreted with caution, as the grouping of these parameters into binary responses (presence/absence) does not consider the quantity, impacts, dates of application of BCA and insecticides and any other parameter influencing their efficacy. Even though many of the growers' control methods were similar, variability was high; thus differences are more difficult to detect.

The influence of plant variety on thrips populations, rather than on host plant tolerance to damage, has been further substantiated in recent literature (Rahman et al. 2010; Abdelmaksoud et al. 2020; Mouden et al. 2021; Souza et al. 2022). The results showing a small relationship between soil cover and the amount of damage done by the thrips population on strawberries could also be explained by the presence of other host plants. Uncovered soil can be a source of unmanaged annual weeds that host thrips, providing an alternative pollen source when strawberry pollen is in short supply. However, this result should be treated with caution because of the low number of plots in the uncovered soil category and the difference in the number of plots between the categories.

Applicability and limitations

Our results are applicable where *F. occidentalis* is predominant; however, they should be considered with caution for other thrips species. This study focused on everbearing strawberry crops. Other studies of thrips populations in Switzerland have shown that, although the dynamics are comparable, results may be different (species present, intensity of attacks) in other strawberry crops (Linder et al. 1998; Höhn et al. 1999). Furthermore, sampling was carried out on flowers, so we cannot rule out the presence of thrips living on the leaves (such as *Echinothrips americanus* or *Scirtothrips* spp.).

Observations were conducted on growers' plots, ensuring practical relevance. However, participation was voluntary, introducing potential selection bias. For statistical power reasons, environmental and management factors were not included in the same models. With the exception of one interaction factor, only additive models were presented. This is a limitation of the study as the interactions between these parameters could be important in explaining some of the variation in thrips populations and damage.

Conclusion

This study represents a significant advancement in our understanding of thrips populations in everbearing strawberry crops in Switzerland. The results confirm that *F. occidentalis* has become the most problematic species, with a marked increase in its impact on yields and that the main results apply to thrips in general and this species. However, other species such as *T. tabaci* and *F. intonsa* also have a role to play in thrips population dynamics. The observed variability of populations between plots was mainly influenced by environmental parameters such as altitude, mean temperature and distance to meadows. Adjustments in integrated pest management strategies, such as the integration of host plants and the management of neighboring habitats, could improve the management of thrips in strawberries. The results also show that, in addition to managing the size of thrips populations to limit their damage to crops, research into feeding behavior and movement within strawberry crops would make it possible to assess the possibility of limiting damage to fruit by providing alternative food sources. All in all, this research opens prospects for better management of thrips populations, highlighting the importance of taking environmental factors and local biodiversity into account in everbearing strawberry production systems.

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Author contributions LSc, VD and LSu conceived the ideas and designed the methodology; LSc and VD collected the data, AM carried out the thrips identifications, LSc analyzed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data availability Any information relating to the study that is not included in the Online Resources or in the article can be requested from the corresponding author (analytic code, dataset, questions, protocols).

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work and conclusions of this study.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

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