agronomy

MDPI

Article

Multi-Year Development and Field Validation of Blended p-Anisaldehyde–Verbenone Lure Systems and Dispenser Technologies for Monitoring Western Flower Thrips

Martyn J. Wood [1,2,*,†,‡], Alexander E. Dearden [1,†], James C. Bull [1], Farooq Shah [2], Owen Jones [3], R. Scott Thomas [1], Henry Frend [1], John Stobart [4], Benjamin J. Clunie [1,5], Zack Saud [6], E. Joel Loveridge [1] and Tariq M. Butt [1,*]

[1] Department of Biosciences, Faculty of Science and Engineering, Swansea University, Swansea SA2 8PP, UK; a.e.dearden@swansea.ac.uk (A.E.D.); j.c.bull@swansea.ac.uk (J.C.B.); robert.s.thomas@swansea.ac.uk (R.S.T.); henryfrend2000@gmail.com (H.F.); bclunie@harper-adams.ac.uk (B.J.C.); e.j.loveridge@swansea.ac.uk (E.J.L.)
[2] Razbio Limited, Enterprise Centre, Bryn Road, Tondu, Bridgend CF32 9BS, UK; f.shah@razbio.com
[3] Lisk & Jones Consultants Ltd., c/o Berry Smith LLP, Brackla House, Brackla Street, Bridgend CF31 1BZ, UK; owenj@plaga.co.uk
[4] John Stobart Org., 19 Butt Lane, Laceby, Derby DN37 7BB, UK; j.stobart@outlook.com
[5] Harper Adams University Entomology Group, Agriculture and Environment Department, Harper Adams University, Newport, Shropshire TF10 8NB, UK
[6] Division of Infection and Immunity, Cardiff University School of Medicine, Cardiff CF14 4XN, UK; saudz@cardiff.ac.uk
* Correspondence: martyn_wood@imbb.forth.gr (M.J.W.); t.butt@swansea.ac.uk (T.M.B.)
† These authors contributed equally to this work.
‡ Current address: Institute of Molecular Biology and Biotechnology, Foundation of Research and Technology Hellas, 70013 Heraklion, Crete, Greece.

Abstract

Western flower thrips (*Frankliniella occidentalis*) are major pests of horticultural crops worldwide, creating a need for sensitive monitoring tools to support integrated pest management. Semiochemical lures are widely used to enhance sticky trap capture, but their effectiveness depends on both attractant composition and dispenser design. In this study, the plant-derived volatiles *p*-anisaldehyde (PANI) and S(−)-verbenone were evaluated as individual and blended attractants, together with the development of practical dispenser systems, across field trials conducted between 2018 and 2021 in commercial strawberry production systems. Initial short-term trials in 2018 showed that both compounds increased trap capture relative to controls, with the PANI–verbenone blend providing the greatest enhancement across repeated 48 h assessments. Follow-on trials in 2019 supported these findings and introduced ethylene vinyl acetate (EVA) tubing as a controlled-release dispenser, improving lure practicality and durability without loss of efficacy. Expanded multi-site trials in 2021, conducted across four farms over four weeks, showed that although early capture dynamics were similar among treatments, differences emerged over time. By day 28, blended attractants, particularly when delivered via polymer-based dispensers, consistently exceeded controls and performed comparably to, or sometimes better than, the commercial standard Lurem-TR. These findings show that combining plant-derived volatile blends with optimised controlled-release dispensers can improve monitoring sensitivity for *F. occidentalis* under commercial growing conditions.

Keywords: western flower thrips; lures; verbenone; p-anisaldehyde; attractant blends; dispensers

Academic Editor: Mayker Lazaro Dantas Miranda

Received: 8 April 2026
Revised: 19 May 2026
Accepted: 22 May 2026
Published: 26 May 2026

1. Introduction

Western flower thrips (WFT), *Frankliniella occidentalis*, are major pests of horticultural and agricultural crops that now have a worldwide distribution [1,2]. Economic losses are large, but with countries such as the Netherlands and the UK alone suffering > $50 million in damages [3], it is suggested that the true cost of WFT infestations globally exceeds $1 billion. These costs are accrued directly through feeding-associated damages and indirectly via disease, especially through tospovirus transmission [4–6]. Compounding these issues is the behaviour of WFT; they are small, cryptic, and have a very broad host–plant range [2,7]. Furthermore, their high generation rate means that low population density can go unrecorded in early parts of the year, leading to a sudden and rapid population explosion; in the UK, this is known to occur in two peak intervals in later spring and mid-summer (personal communication with growers). This is compounded by increasing resistance to several critical chemical insecticides [8], including Spinosad, which is now often largely ineffective at the recommended dosages [9–11]. As such, management strategies rely heavily on monitoring programs to identify WFT presence at the earliest possible stage for effective management, driving the need for the development of high-sensitivity lures that will work in the early season.

Current monitoring practices generally use coloured sticky traps, often blue or yellow, in conjunction with lures that enhance the capability of the traps to capture active WFT [12–15]. Research has begun to advance the efficacy of the colouring applied to the sticky cards to increase innate capture [16,17], with a recent study using ocular data from thrips to identify the optimal trap colouring for increased capture rates [17]. Although sticky traps are widely used, their sensitivity and relationship to population density and crop damage can be limited, particularly at low pest densities [18], necessitating the use of attractive lures to enhance sensitivity and capture. At present, the primary commercial attractant used is Lurem-TR (Koppert BV, Berkel en Rodenrijs, The Netherlands), a formulated methyl-isonicotinate product used as an aggregation kairomone [19]. This compound and the product are highly effective across broad agro-systems; nevertheless, they are still subject to performance variability due to specific conditions within the different agricultural and trapping systems at play [12,19]. The fact that WFT oviposit and feed on a wide variety of plant species suggests they are responding to a diverse range of plant-derived volatiles, opening the door for the development of multi-component lures that could be suited to variable conditions. Indeed, several excitatory plant volatiles have been identified, with some showing considerable promise as lures [20–23]. Among the most promising described plant-derived thrips attractants are p-anisaldehyde (PANI) and verbenone, both of which have been identified in silico and in vitro [23,24]. Both are now known to significantly increase trap capture as singular compounds [23,25–27], making them excellent candidates for deployment in monitoring and mass trapping programmes as a means to accentuate and enhance the local chemosphere to direct insect pest behaviours.

Verbenone is a monoterpene found in a wide range of plant species, including Spanish verbena, rosemary, eucalyptus, magnolia, phlox, and pine pollen [28–30]. Like PANI, it is a common additive in products as a fragrance or flavouring agent. It is used as a fragrance and a flavour ingredient [28,31]. Verbenone is also a well-known semiochemical acting on a range of insect pest species; most notably, it works as an anti-aggregation pheromone in the bark beetle *Dendroctonus ponderosae*, synthesised by mutualistic yeasts within the insect system [32–34]. Meanwhile, PANI, also known as 4-methoxybenzaldehyde, is found in the essential oils and extracts of vanilla, magnolia, pear, fennel, cranberry, blackcurrant, cinnamon, basil, and a range of woodland tree species [35–38]. As a result of its floral odour profile, PANI is widely used in the perfume and food flavouring industries [38]. It is known to influence the behaviour of several insect species, acting as an attractant for some

pollinators but a repellent of ants [39]. With regards to thrips, PANI is also known to act as an effective kairomonal attractant for species, including *Frankliniella tenuicornis* and *F. intonsa* [40], *F. occidentalis* [22], and *Limothrips cerealium* [40,41]. Given their commonality as plant emanations, they are liable to be key signals used by WFT during the early stages of the year when suitable food sources become available. This facet potentially makes them useful as a combination application to overcome the issues of habituation that are known for single-compound applications, and their food source mimicry may facilitate more sensitive capture rates at early stages of the year when flowering in the crop is at minimal levels.

The application method for any given semiochemical attractant is also a primary consideration for effective deployment. Release rates, longevity, and environmental stability determine the concentration and temporal consistency of behaviourally active volatiles [42]. Effective dispensers must maintain emissions, as best as possible, within biologically relevant thresholds over extended periods and within the variability of the natural environment. In practice, this means avoiding both rapid depletion and sub-threshold release that can reduce trap sensitivity [43–45]. Release kinetics are strongly influenced by dispenser material and design, with systems such as polyethylene vials, rubber septa, and polymer matrices exhibiting distinct diffusion profiles that must be matched to the volatility and stability of the active compounds [46,47]. Environmental factors, including temperature, UV exposure, and airflow, further modulate emission rates and plume structure, often leading to substantial variation in field performance if not accounted for during optimisation [48–50]. In addition, inconsistent or excessive release can contribute to reduced behavioural responses over time [51,52], albeit these diminished responses are variable and seemingly system-specific [53]. Taken together, these lines of evidence highlight the importance of controlled, sustained emission profiles in maintaining lure efficacy under field conditions and showcase the need for optimised dispenser development and deployment [54].

While both p-anisaldehyde and verbenone have previously been identified as behaviourally active semiochemicals in *Frankliniella occidentalis* [22,23], their combined application, temporal performance under field conditions, and integration with practical delivery systems remain poorly understood. In particular, the potential for blended plant-derived volatiles to provide sustained enhancement of trap capture, rather than short-term attraction alone, has not been systematically evaluated. This study, therefore, moves beyond single-compound assessments to examine (i) the performance of a p-anisaldehyde–verbenone blend, (ii) the influence of controlled-release dispenser technologies on lure efficacy over time, and (iii) the consistency of these effects across multiple commercial production sites. By linking attractant composition with optimised release strategy and field-scale validation, this work aims to establish a more robust framework for semiochemical-based monitoring of WFT within integrated pest management systems.

2. Materials and Methods

2.1. Lure and Dispenser Preparations

The putative attractants, *p*-Anisaldehyde (98%, Sigma Aldrich, Gillingham, UK) and S-(−)-verbenone (93%, Sigma Aldrich, Gillingham, UK), were prepared for the trials onsite at Swansea University. Several preparations were made as the trials advanced; firstly, using basic cellulose-pad lures for the initial developmental trials during 2018 and 2019, before more advanced polymers were developed for the dispenser trials throughout 2021.

For the initial development trials, two materials were assessed as initial delivery systems: 30 mm × 30 mm condensed cellulose pads (Agrisense Ltd., Pontypridd, UK) and 10 mm × 85 mm EVA tubing (1 mm thickness, 6 mm external diameter, Rainbow Ltd., Hull, UK). Cellulose pads had the attractive compound applied to the cellulose before

being placed inside a perforated polypropylene sachet. EVA tubes, by contrast, were sealed at one end using Mac Allister clear glue sticks (Mac Allister, Cambridge, UK) before the liquid attractants were pipetted into the tube and the opposing ends were sealed. Lures were prepared as singular or combined preparations: verbenone only, p-anisaldehyde only, and an equal combination of the two. In all cases, 1 mL total volume of the attractive compounds was applied within the dispenser. All preparations were then sealed inside airtight foil packaging materials and refrigerated at 4 ± 1 °C until the day of use. Cellulose pads were featured in both sets of experiments, whereas EVA tubing was featured only in the 2019 experiment. Negative control lures, without any attractant application, were prepared in the same manner, whereas commercially prepared Lurem-TR (Koppert BV, The Netherlands) was obtained directly from the manufacturer as a positive control.

For the follow-on trials during the spring and summer of 2021, ethylene vinyl acetate (EVA) tube preparations were retained for comparison against a further two dispenser preparations. A proprietary extruded polymer was provided by Razbio Ltd. (Razbio Ltd., Bridgend, UK) that was given the name 'chewing gum' for the purpose of analysis. This was prepared offsite according to Razbio Ltd. commercial procedures, as well as new versions of the EVA tube dispensers, prepared in the same manner as during the 2019 trials, which were also provided by Razbio Ltd. Primarily as a result of COVID-19-induced supply chain issues, EVA tube dispensers were only available for the first three trials, Homefield Farm, Little Mockbeggar Farm, and Goose Farm, whereas the extruded polymers were only available for the latter two trials, Goose Farm and the EC Drummond site. In addition to these EVA tube and 'chewing gum' dispensers, commercially available 'blister pack' dispensers (Russell IPM, Deeside, UK) were prepared by Russell IPM and obtained for the project for full comparison; these lures were available for use at all trial sites. All of these dispensers were prepared using the same chemicals and volumes as per the 2019 field trials, with a total of 1 mL of attractant compound or blend per dispenser. As with the previous trials, Lurem-TR (Koppert BV, The Netherlands) was used and obtained directly from Koppert BV for use as a positive control.

2.2. Blend and EVA Tube Dispenser Developmental Trials in 2018 and 2019

Field evaluations were conducted across three phases (2018, 2019, and 2021) within commercial strawberry (*Fragaria* × *ananassa*) production systems under polytunnel cultivation in the United Kingdom. The first trial, in 2018, was used to evaluate the efficacy of the blended compounds p-anisaldehyde and verbenone, while the 2019 trial included the development of EVA tube dispensers for the product. For all trials, blank, blue sticky traps measuring 100 mm × 245 mm (Agrisense Ltd., UK) were used as the trap cards.

The initial trials (2018–2019) were conducted at N.I. Cockburn Ltd., Kings Caple, Herefordshire, UK (51°57′38.6″ N, 2°38′45.6″ W). Three polytunnels (8 m × 190 m) were used as experimental arenas, each containing five parallel elevated crop rows. The two outermost rows, spaced approximately 6 m apart, were selected for trap deployment to maximise spatial separation between treatment lines, reduce the likelihood of treatment interference among baited sticky traps, and maintain consistency and comparability between the trials and within the confines of the available polytunnels. These designs are consistent with previous thrips semiochemical field studies that used metre-scale trap spacing to minimise interaction among lure treatments [18,55]. Within each row, traps were positioned at 6 m intervals, and treatments were randomly assigned and re-randomised at each assessment period. These trials were conducted with repeated short-term (48 h) exposure periods used to evaluate attractant performance and optimise formulation.

Prior to each trial, blank blue sticky traps (100 mm × 245 mm, Agrisense Ltd., UK) were deployed to assess WFT capture prior to the introduction of lures. After 48 h, blank

traps were replaced with new traps containing a randomly assigned treatment or control. Traps containing treatments or controls were replaced and re-randomised every 48 h for 8 days, forming 4 assessment periods. When completed, blank sticky traps were put out across the 3 tunnels to assess WFT capture post-removal of lures. In 2018, 9 lure combinations and 3 control treatments were evaluated using condensed cellulose pads (3 cm × 3 cm) as dispensers. There were five replicates of each treatment per polytunnel across 3 separate polytunnels. Traps were spaced 6 m apart within and between rows of strawberry crops.

The study was repeated in 2019 with some modifications. The key differences were the addition of the newly developed EVA tube dispensers and the use of only neat applications and blends due to positive results in 2018. The study duration was also reduced to two 48 h assessments to accommodate agronomic practices during the high-point of the season while still allowing for effective assessment of the dispenser prototype.

2.3. Dispenser Development Field Trials, 2021

Building on these preliminary trials, four independent field experiments were conducted in 2021 at commercial sites across the United Kingdom, encompassing a broader range of environmental conditions and population densities. Trials were conducted at Homefield Farm, Kent, UK, in April (51°24′1.1″ N, 0°13′20.8″ E), Little Mockbeggar Farm, Rochester, UK, in May (51°25′13.9″ N, 0°29′17.2″ E), Goose Farm, Canterbury, UK, in June (51°18′31.2″ N, 1°6′23.4″ E), and EC Drummond, Ross-on-Wye, UK, in August (51°53′55.1″ N, 2°36′53.2″ W).

All 2021 trials were conducted within commercial polytunnels under standard grower management practices. At each site, experimental units consisted of two parallel crop rows within each polytunnel, with traps deployed 20 cm above crop canopy height. Treatments were randomly assigned along each row to minimise positional bias, and spacing between traps was standardised at 6 m between all traps to ensure comparable exposure across treatments. At Homefield Farm, Little Mockbeggar Farm, and Goose Farm, six polytunnels were used per site, organised into three technical replicates comprising two polytunnels per technical replicate. At EC Drummond, three larger polytunnels were used, each representing a single technical replicate due to increased tunnel size and crop area. This design enabled replication at the polytunnel level while maintaining compatibility with commercial production systems.

Traps and lures were deployed simultaneously, with lures attached centrally at the top of each trap, and they remained in place for a continuous four-week period at each site. Thrips capture was recorded at regular intervals, daily for the first seven days and subsequently at days 14, 21, and 28, allowing both short-term accumulation dynamics and longer-term cumulative capture to be assessed. Data were aggregated as cumulative thrips counts per trap over the full 28-day period.

No pesticides were used in any of the tunnels for at least 4 weeks prior to experimentation or during the experimental period. Foliar feed sprays of the crops were conducted once at each site, during which traps were briefly removed to allow for mechanised spraying before being replaced within 2 h. Environmental conditions, including temperature and relative humidity, were not experimentally controlled but reflected typical commercial polytunnel conditions at each site and time point. The sequential timing of the 2021 trials, spanning early spring to late summer, enabled assessment of lure performance across seasonal variation in thrips population dynamics.

A limited subset of the Goose Farm 2021 dataset, comprising the EVA tube preparations for p-anisaldehyde, verbenone, and empty tube controls, was previously reported as part of a confirmatory field trial component in Zafar et al. (2025) [24]. The present manuscript is

the first to present the full multi-year dataset and integrated analysis spanning 2018, 2019, and all four 2021 commercial field trials, including additional sites, treatments, dispenser systems, spatial analyses, and long-term comparative evaluation.

2.4. Statistical Analysis and Data Processing

For all trials (2018, 2019, 2021), heatmaps of thrips counts were generated to visualise spatial distributions within polytunnels. To assess spatial structuring in trap capture, Moran's I statistics were calculated using trap coordinate data. Longitude and latitude coordinates were used to construct a spatial weights matrix based on nearest neighbours (k = 5) using the *spData* package [56].

For all trials, hypotheses were tested on the relative efficacies of different attractant, concentration, and dispenser combinations (specific to the trial) using generalised linear mixed effects models (GLMMs). Integer thrips catch responses were modelled as negative binomial distributions, with natural logarithm link functions. Since not all combinations of attractant and dispenser were used, we fitted realised combinations as a single, categorical fixed effect, interacting with log(time) where appropriate. We assessed differences between combinations primarily through 95% confidence intervals (CIs) on parameter estimates. Where appropriate, the statistical results were interpreted with significance thresholds set at $\alpha \leq 0.05$. The hierarchical trial design was modelled as nested random effects: Farm/Farm Replicate/Tunnel/Row/Treatment Replicate (specific to the trial). We modelled spatial autocorrelation at the individual tunnel level using a Matérn function of Easting and Northing values at the metre scale.

For the 2021 trials, catches were recorded daily up to day seven and then on days 14, 21, and 28. We modelled the daily trajectories (1–7) and final catch (28) using separate models. This allowed us to model temporal autocorrelation over the initial period where time points were regularly spaced, fitting an AR1 process to per-treatment replicate time series. On day 28, there was only one time point recorded, so this lowest level of the experimental hierarchy was not modelled explicitly but rather formed the residual term.

All statistical analyses were undertaken using R version 4.5.1 [57]. GLMMs were fitted using the *glmmTMB* package [58]. Additional packages for data wrangling and presentation were *dplyr* [59], *emmeans* [60], *flextable* [61], *ggplot2* [62], *officer* [63], *scales* [64], and *sf* [65].

3. Results

3.1. Blend Development Field Trial, 2018

Across the entire 2018 study, 9872 *F. occidentalis* were captured on blue sticky traps. Mean WFT capture varied across assessment periods. The lowest capture rates were recorded on unbaited sticky traps during the 0–48 h period prior to (930) and following (447) semiochemical evaluation. Subtle differences in WFT capture between polytunnels were observed, with generally higher numbers in PT3, followed by PT2 and then PT1. Within polytunnels, capture was typically highest at the mouths of each tunnel (Figure 1).

All experimental treatments caught significantly higher numbers of thrips than the control group (log odds ranged from 0.574 for 1% PANI to 1.16 for 100% PANI–verbenone blend, $p < 0.001$ in all cases). On average, PANI–verbenone blends caught more WFT than any other treatment, particularly at the 100% concentrations (Figure 2A). Thrips capture using Lurem-TR was significantly higher than the control group (log odds = 0.863, $p < 0.001$) but statistically similar to other treatments (Figure 2A, 95% C.I.s). Mineral oil did not attract significantly more WFT than controls (log odds = 0.215, $p = 0.11$).

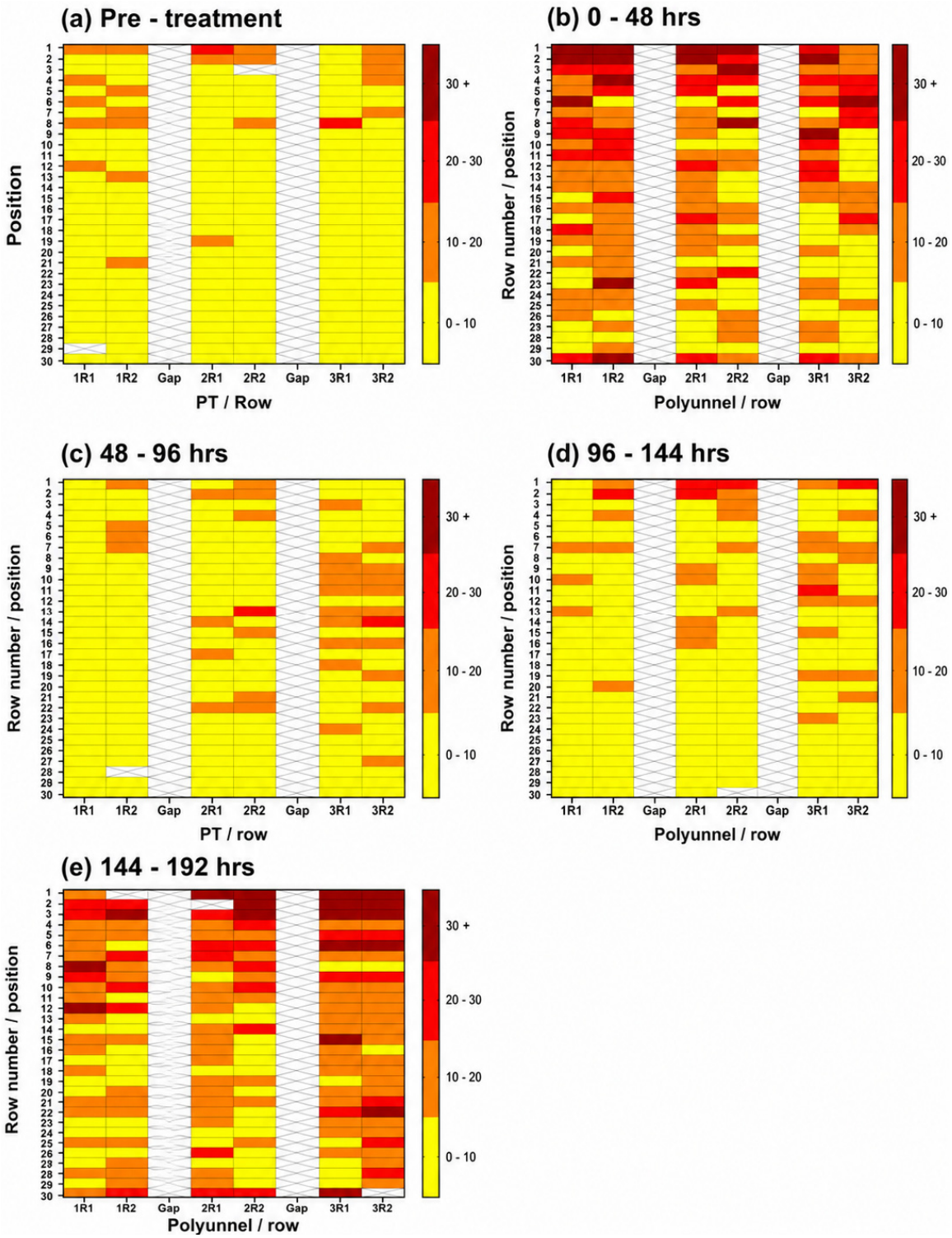

Figure 1. Spatial–temporal distribution of *Frankliniella occidentalis* during 2018 field trials. Heatmaps show adult *F. occidentalis* captured on blue sticky traps across experimental polytunnels over sequential sampling periods: (**a**) pre-treatment, (**b**) 0–48 h, (**c**) 48–96 h, (**d**) 96–144 h, and (**e**) 144–192 h following lure deployment. The *x*-axis represents trap position by polytunnel and row (gaps between tunnels indicated by hatched cells), and the *y*-axis denotes relative trap position along rows. Cell colour indicates the number of thrips captured per trap using a discrete scale; 0–10 (yellow), 10–20 (orange), 20–30 (red), >30 (dark red). Hatched cells represent non-sampled positions and gaps between polytunnels. Spatial patterns show initially low and heterogeneous capture prior to treatment, followed by increased abundance and the emergence of spatial structure over time, with higher captures frequently observed near polytunnel edges and variable gradients along tunnel length.

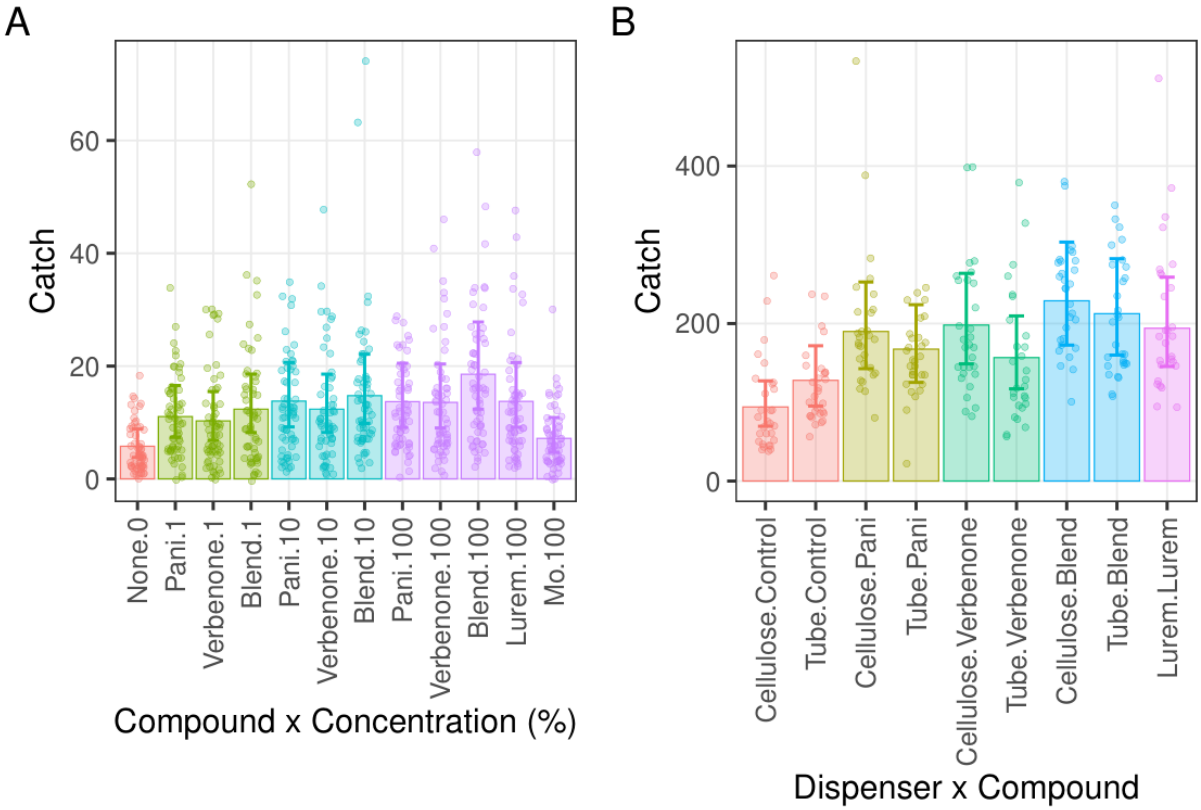

Figure 2. Mean *Frankliniella occidentalis* capture per trap. Treatments include blended p-anisaldehyde + verbenone ("Blend"); p-anisaldehyde alone ("Pani"); verbenone alone ("Verbenone"); and control treatments consisting of no application ("None") or mineral oil ("Mo"). These were also compared against the industry standard of Lurem-TR. Panel (**A**) 2018 field trials. Treatments were applied at three concentrations, 1%, 10%, or 100%, using cellulose pad dispensers. Colour coding indicates different concentrations. Panel (**B**) 2019 field trials. Treatments were formulated in cellulose ("Cellulose") or EVA tubing ("Tube") dispensers. Colour coding indicates different attractants. Bars represent mean (±95% C.I. error bars). Points represent observed trap counts.

3.2. EVA Tube Dispenser Development Field Trial, 2019

Across the entire study, 50,970 *Frankliniella occidentalis* and 109 *Aeolothrips intermedius* adults were captured on blue sticky traps. The lowest WFT capture rate was recorded during the 0–48 h control period (4982), followed by assessment 1 (18,954) and assessment 2 (27,034). Generally, more WFT were caught in PT1, followed by PT2 and then PT3, although variation was observed across time points. Within polytunnels, WFT capture was typically higher at tunnel entrances (Figure 3). As the study progressed, WFT appeared to shift from west to east, moving from PT3 towards PT2 and PT1. Due to agronomic requirements, the study was terminated after completion of assessment 2.

On average, attractant treatments resulted in higher WFT capture compared to control groups, independent of dispenser type (log odds ranged from 0.510 for verbenone from EVA tube dispensers to 0.889 for blended treatments from tube dispensers, $p < 0.001$ in all cases). Although cellulose pad dispensers tended to result in higher capture than EVA tubes for blended treatments, this difference was not statistically significant (Figure 2B, 95% C.I.s). Lurem-TR also resulted in higher capture than both control groups but was comparable to all other treatments (Figure 2B, 95% C.I.s).

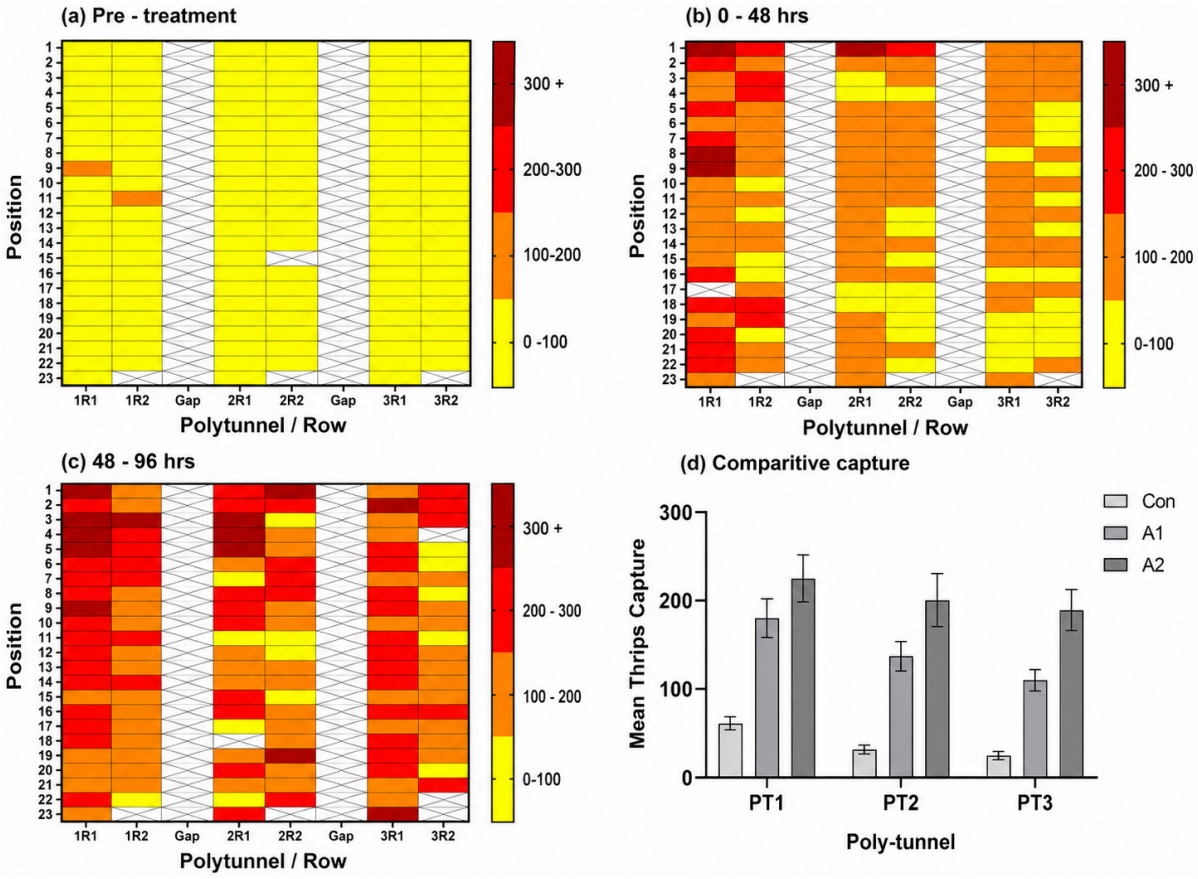

Figure 3. Spatial distribution and comparative capture of *Frankliniella occidentalis* during 2019 field trials. Heatmaps show adult *F. occidentalis* captured on blue sticky traps across polytunnels at (**a**) pre-treatment, (**b**) 0–48 h, and (**c**) 48–96 h following lure deployment. The *x*-axis represents trap position by polytunnel and row, with gaps between tunnels indicated by hatched cells, and the *y*-axis denotes relative position along rows. Cell colour indicates thrips capture per trap using a discrete scale: 0–100 (yellow), 100–200 (orange), 200–300 (red), >300(dark red), with hatched cells representing non-sampled positions. Panel (**d**) shows mean (±SE) thrips capture per polytunnel (PT1–PT3) across treatments: control (Con), assessment 1 (A1), and assessment 2 (A2). Capture was low prior to treatment but increased markedly following lure deployment, with clear spatial structuring emerging over time and consistently higher trap counts observed across treated assessments relative to controls.

3.3. Development Field Trials, 2021

Over the initial seven days of the trials, cumulative thrips catch increased with time according to a power–law relationship, appearing as a linear trend on a log–log scale (Figure 4). Model fits from the negative binomial GLMM closely tracked observed values across all farms and treatments. Towards the latter part of this period (days 4–7), the rate of increase began to decline in several cases, although cumulative catch continued to rise. Estimates of the initial rate of accumulation (Table 1) were broadly similar across realised attractant–dispenser combinations within each site, with extensive overlap in 95% confidence intervals (CIs). At EC Drummond, slopes ranged from 0.247 to 0.308, while at Mockbeggar, they ranged from 0.231 to 0.282. Goose Farm exhibited higher accumulation rates overall (0.388–0.490), whereas Homefield Farm showed lower and more variable rates (e.g., 0.266 ± 0.099 for controls), reflected in wider confidence intervals. Across all sites, there was no clear separation among attractant–dispenser combinations during the early phase, with overlapping confidence intervals indicating no detectable differences between treatments.

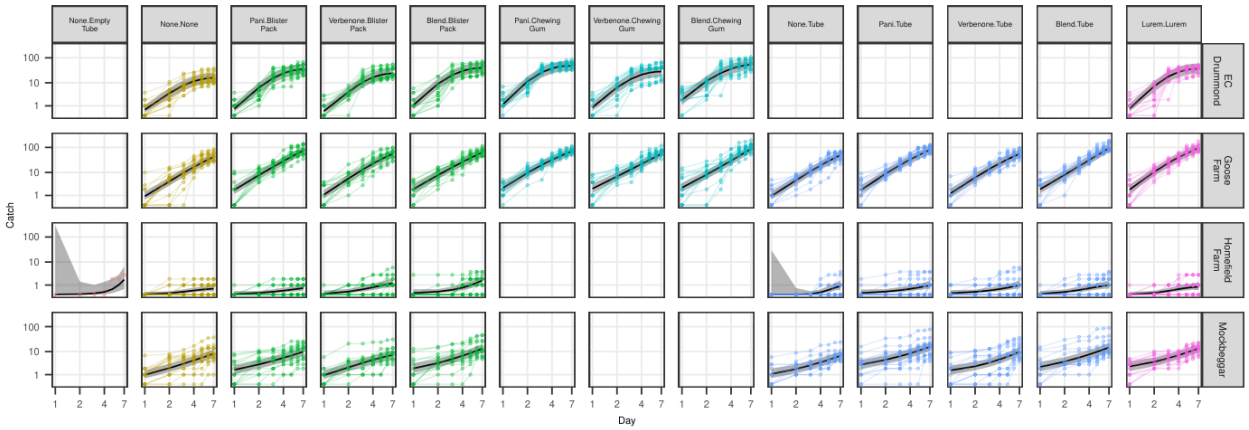

Figure 4. Temporal dynamics of *Frankliniella occidentalis* capture across treatments and sites during 2021 field trials. Panels show cumulative mean (±95% C.I.) adult *F. occidentalis* captured per blue sticky trap over time (days 1–7) for each treatment and dispenser type across four commercial sites (EC Drummond, Goose Farm, Homefield Farm, and Mockbeggar). Treatments include p-anisaldehyde (PANI), verbenone (V), and blended PANI + verbenone, deployed using blister packs, chewing gum matrices, and EVA tube dispensers, alongside control treatments and the commercial lure Lurem-TR. Points represent observed trap counts, with fitted lines indicating temporal trends in capture. Differences in slope and magnitude reflect variation in lure performance, dispenser type, and site-specific conditions over the sampling period.

Table 1. Initial rate of thrips accumulation with realised combinations of attractants and dispersers.

Farm	Treatment	Slope	SE	Lwr 95%	Upr 95%
EC Drummond	None.None	0.258	0.022	0.215	0.302
	Pani.Blister Pack	0.307	0.017	0.273	0.342
	Verbenone.Blister Pack	0.308	0.019	0.270	0.346
	Blend.Blister Pack	0.259	0.017	0.226	0.293
	Pani.Chewing Gum	0.247	0.015	0.218	0.277
	Verbenone.Chewing.Gum	0.260	0.018	0.226	0.295
	Blend.Chewing.Gum	0.281	0.015	0.253	0.310
	Lurem.Lurem	0.283	0.017	0.249	0.317
Goose Farm	None.None	0.446	0.018	0.411	0.481
	Pani.Blister Pack	0.449	0.015	0.420	0.478
	Verbenone.Blister Pack	0.448	0.017	0.414	0.482
	Blend.Blister Pack	0.412	0.015	0.382	0.442
	Pani.Chewing Gum	0.388	0.014	0.360	0.416
	Verbenone.Chewing Gum	0.415	0.015	0.385	0.445
	Blend.Chewing Gum	0.476	0.014	0.448	0.503
	None.Tube	0.458	0.018	0.423	0.493
	Pani.Tube	0.429	0.014	0.402	0.456
	Verbenone.Tube	0.428	0.017	0.395	0.462
	Blend.Tube	0.490	0.014	0.463	0.516
	Lurem.Lurem	0.422	0.014	0.396	0.449
Homefield Farm	None.Empty Tube	0.776	0.361	0.069	1.482
	None.None	0.266	0.099	0.073	0.460
	Pani.Blister Pack	0.272	0.099	0.077	0.466
	Verbenone.Blister Pack	0.288	0.075	0.142	0.435
	Blend.Blister Pack	0.373	0.073	0.231	0.516
	None.Tube	0.984	0.417	0.166	1.802
	Pani.Tube	0.248	0.077	0.098	0.399
	Verbenone.Tube	0.276	0.073	0.133	0.418
	Blend.Tube	0.272	0.079	0.116	0.427
	Lurem.Lurem	0.295	0.091	0.118	0.473

Table 1. *Cont.*

Farm	Treatment	Slope	SE	Lwr 95%	Upr 95%
Mockbeggar	None.None	0.273	0.028	0.219	0.328
	Pani.Blister Pack	0.241	0.026	0.191	0.291
	Verbenone.Blister Pack	0.231	0.030	0.171	0.290
	Blend.Blister Pack	0.274	0.024	0.228	0.321
	None.Tube	0.258	0.033	0.193	0.323
	Pani.Tube	0.247	0.022	0.204	0.290
	Verbenone.Tube	0.282	0.026	0.231	0.333
	Blend.Tube	0.268	0.023	0.224	0.312
	Lurem.Lurem	0.254	0.025	0.205	0.303

By day 28, cumulative thrips catch differed among treatments (Figure 5), with model-derived estimates presented in Table 2. At E. C. Drummond, the control treatment (log mean = 4.265, 95% C.I.: 4.024–4.506) was lower than all attractant treatments, with the highest values observed for the blend delivered via chewing gum (5.350, 95% C.I.: 5.115–5.586) and Lurem-TR (5.221, 95% C.I.: 4.982–5.459), both showing non-overlapping confidence intervals with the control. At Goose Farm, control catches (4.640, 95% C.I.: 4.442–4.838) were exceeded by several treatments, including blend in tube dispensers (5.558, 95% C.I.: 5.362–5.753) and Lurem-TR (5.439, 95% C.I.: 5.244–5.634), again with non-overlapping confidence intervals relative to the control. At Mockbeggar, the control (3.797, 95% C.I.: 3.583–4.012) was lower than treatments, such as blend in tube dispensers (4.867, 95% C.I.: 4.659–5.076), with separation of confidence intervals indicating differences in catch. In contrast, Homefield Farm exhibited substantially lower overall catch across all treatments (log means: 1.582–2.785), and only the blended attractant (e.g., in tube: 2.785, 95% C.I.: 2.543–3.027; in blister pack: 2.546, 95% C.I.: 2.291–2.800) and Lurem-TR (2.379, 95% C.I.: 2.115–2.644) showed non-overlapping confidence intervals relative to the control (1.582, 95% C.I.: 1.275–1.888), while other treatments overlapped with the control.

Visualisation of data indexed by spatial coordinates and experimental hierarchy showed consistent patterns of accumulation across rows, tunnels, and replicates within sites, with no evident systematic spatial bias in treatment performance. Moran's I analysis indicated the presence of spatial structuring in trap capture, with clear site-specific differences in both magnitude and temporal dynamics. Strong and consistent positive spatial autocorrelation was observed at Mockbeggar and Goose Farm ($I \approx 0.3$–0.47), indicating pronounced clustering of trap captures throughout the sampling period. In contrast, a weaker but dynamic spatial structure was observed at Homefield and EC Drummond. At Homefield, Moran's I increased progressively during the first week (peaking at ~0.22 on day 7), before declining during later assessments, suggesting an initial aggregation phase followed by a more homogeneous distribution of thrips across the system. At EC Drummond, spatial structuring was minimal during early sampling points but increased in later weeks (up to ~0.23 by day 28), indicating a delayed emergence of spatial organisation.

These patterns are consistent with the spatial–temporal dynamics observed in heatmaps (Figures 6–9), where early stochastic capture gave way to increasingly structured distributions over time. Collectively, these findings demonstrate that both the strength and timing of spatial clustering vary across commercial production systems, likely reflecting differences in population density, tunnel configuration, and local dispersal behaviour.

Consistent with these empirical patterns, we found that Matérn spatial correlation within individual tunnels was a substantially better statistical fit than independent locations: days 1—7 model, ΔAICc = 2475; day 28 model, ΔAICc = 160.2.

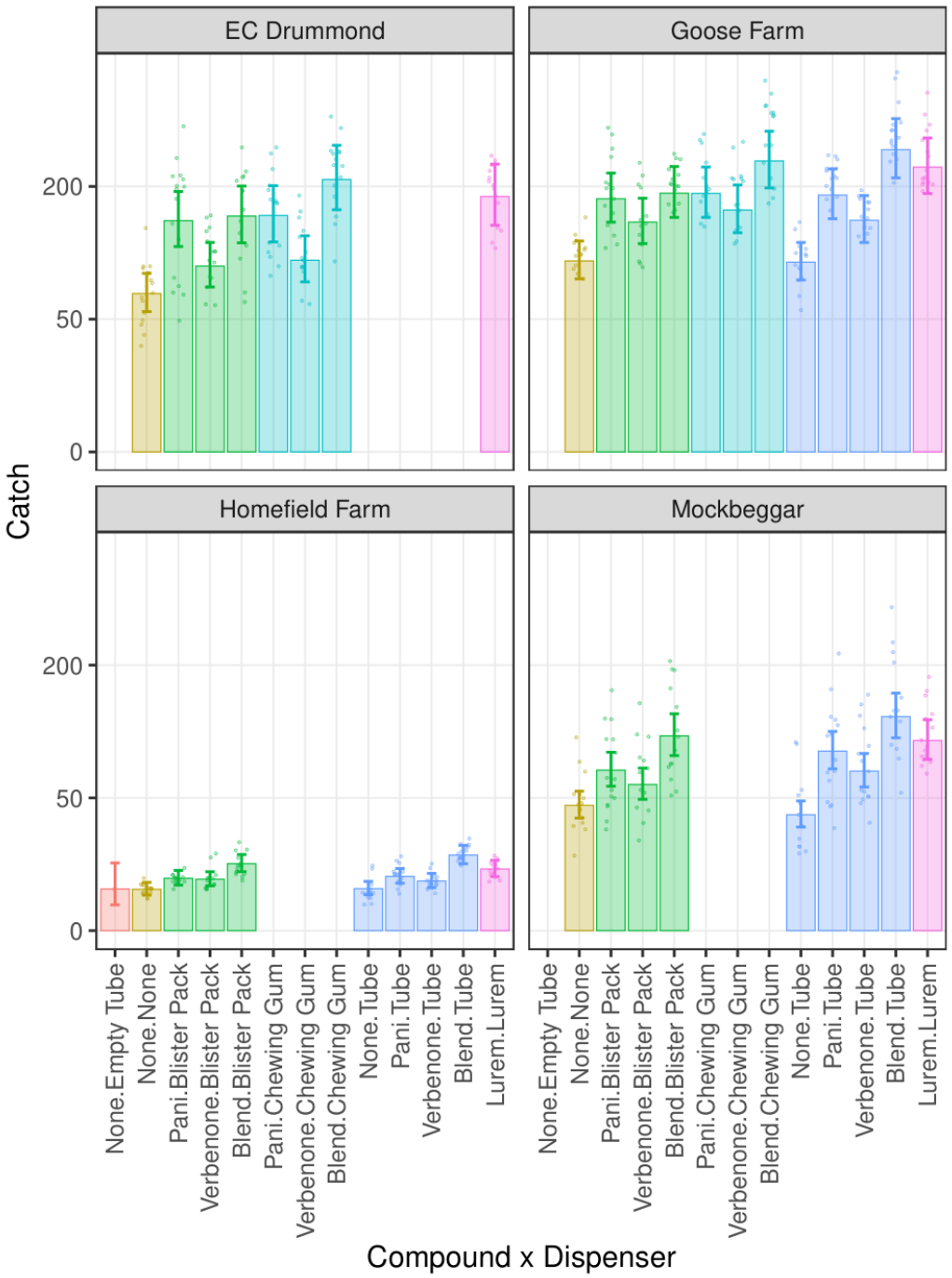

Figure 5. Mean *Frankliniella occidentalis* capture per trap across treatments and sites during 2021 field trials. Bars represent mean (±95% C.I.) numbers of adult *F. occidentalis* captured per blue sticky trap 28 days after the trial began for each treatment across four commercial sites: EC Drummond, Goose Farm, Homefield Farm, and Mockbeggar. Treatments include p-anisaldehyde (PANI), verbenone, and blended PANI + verbenone deployed using blister pack, chewing gum, and EVA tube dispensers, alongside unloaded controls and the commercial lure Lurem-TR. Colour coding indicates different dispenser types; red (controls, green (blister pack), turquoise (chewing gum), blue (tubes). Points represent individual trap counts. Differences in capture reflect variation in treatment performance, dispenser type, and site-specific conditions.

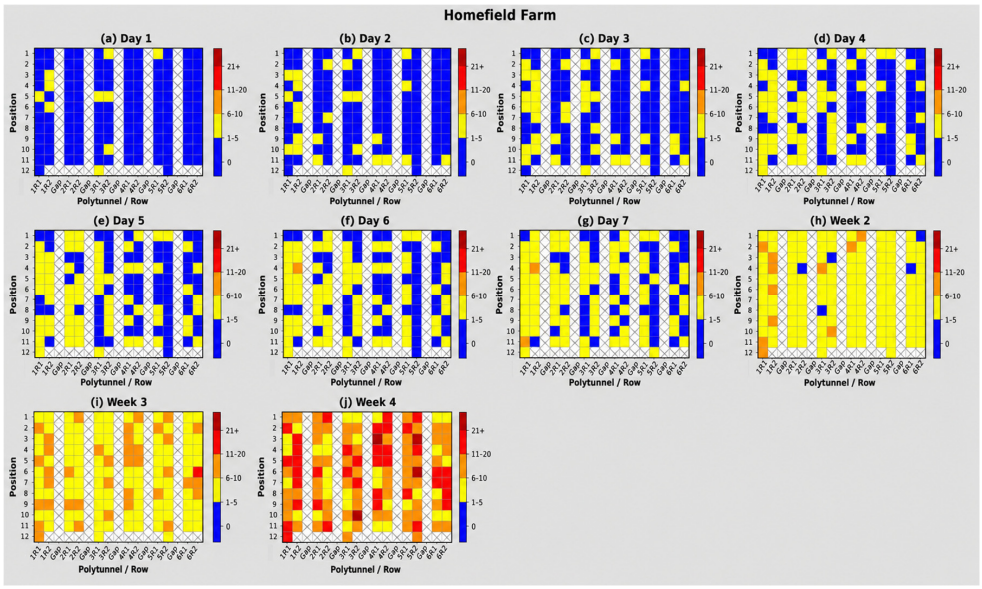

Figure 6. Spatial–temporal distribution of *Frankliniella occidentalis* at Homefield Farm, WC Chambers, Kent, UK. Heatmaps show adult *F. occidentalis* captured on blue sticky traps at Homefield Farm, Kent, UK, throughout the four-week trial in April 2021. Subplots (**a**–**j**)represent sampling at days 1–7 and weeks 2–4 following lure deployment. The *x*-axis indicates trap position by polytunnel and row (gaps between tunnels hatched), and the *y*-axis denotes relative position along rows. Cell colour represents thrips capture per trap using a discrete scale: 0 (blue), 1–5 (yellow), 6–10 (orange), 11–20 (red), and >21 (dark red). Hatched cells indicate non-sampled positions. Across sites, captures were typically highest at polytunnel entrances and became more spatially structured over time, with increasing abundance in later assessments.

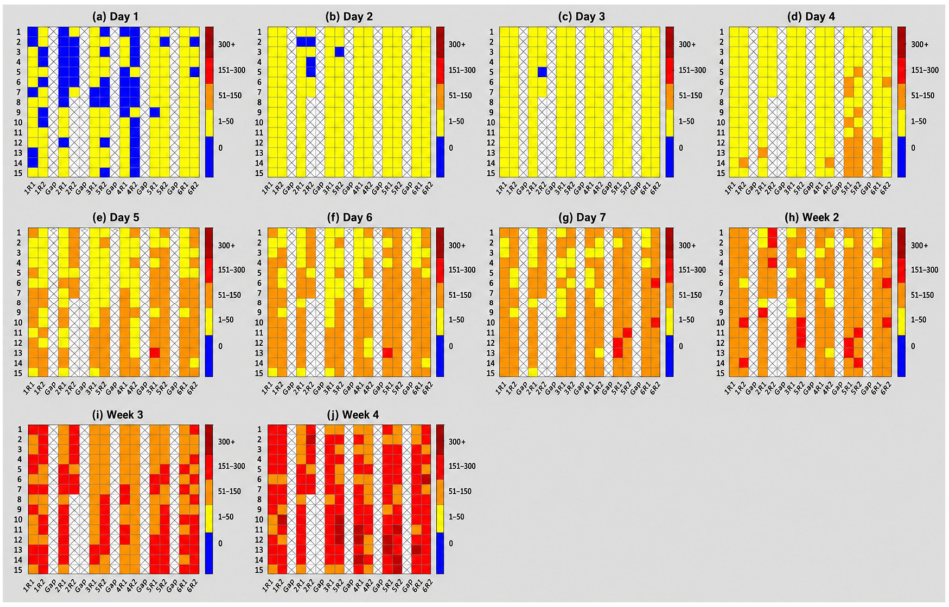

Figure 7. Spatial–temporal distribution of *Frankliniella occidentalis* at Little Mockbeggar Farm, WC Chambers, Rochester, UK. Heatmaps show adult *F. occidentalis* captured on blue sticky traps at Little Mockbeggar Farm, Rochester, UK. Subplots (**a**–**j**) represent sampling at days 1–7 and weeks 2–4 following lure deployment. The *x*-axis indicates trap position by polytunnel and row (gaps between tunnels hatched), and the *y*-axis denotes relative position along rows. Cell colour represents thrips capture per trap using a discrete scale: 0 (blue), 1–50 (yellow), 51–150 (orange), 151–300 (red), and >300 (dark red). Hatched cells indicate non-sampled positions. Across sites, captures were typically highest at polytunnel entrances and became more spatially structured over time, with increasing abundance in later assessments.

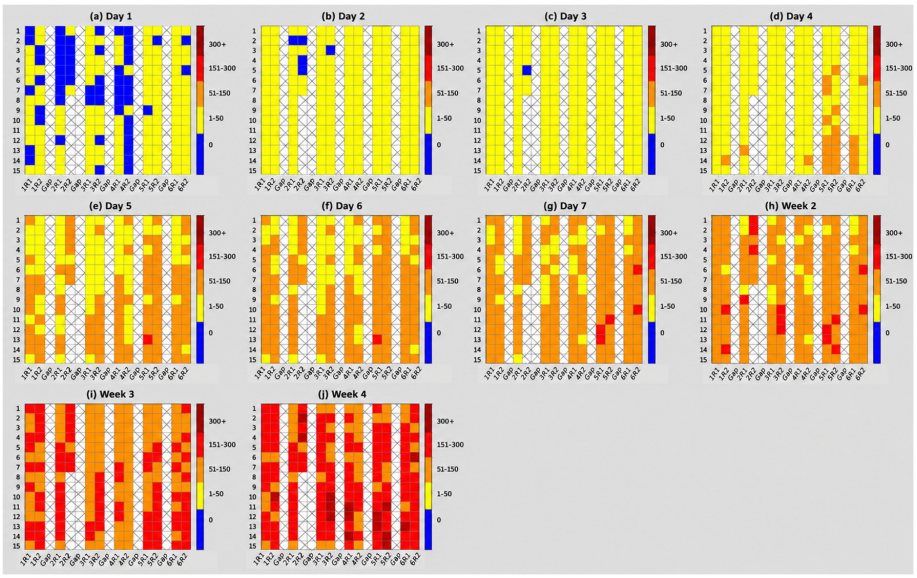

Figure 8. Spatial–temporal distribution of *Frankliniella occidentalis* at Goose Farm, WC Chambers, Canterbury, UK. Heatmaps show adult *F. occidentalis* captured on blue sticky traps at Goose Farm, Canterbury, UK. Subplots (**a–j**) represent sampling at days 1–7 and weeks 2–4 following lure deployment. The *x*-axis indicates trap position by polytunnel and row (gaps between tunnels hatched), and the *y*-axis denotes relative position along rows. Cell colour represents thrips capture per trap using a discrete scale: 0 (blue), 1–50 (yellow), 51–150 (orange), 151–300 (red), and >300 (dark red). Hatched cells indicate non-sampled positions. Across sites, captures were typically highest at polytunnel entrances and became more spatially structured over time, with increasing abundance in later assessments.

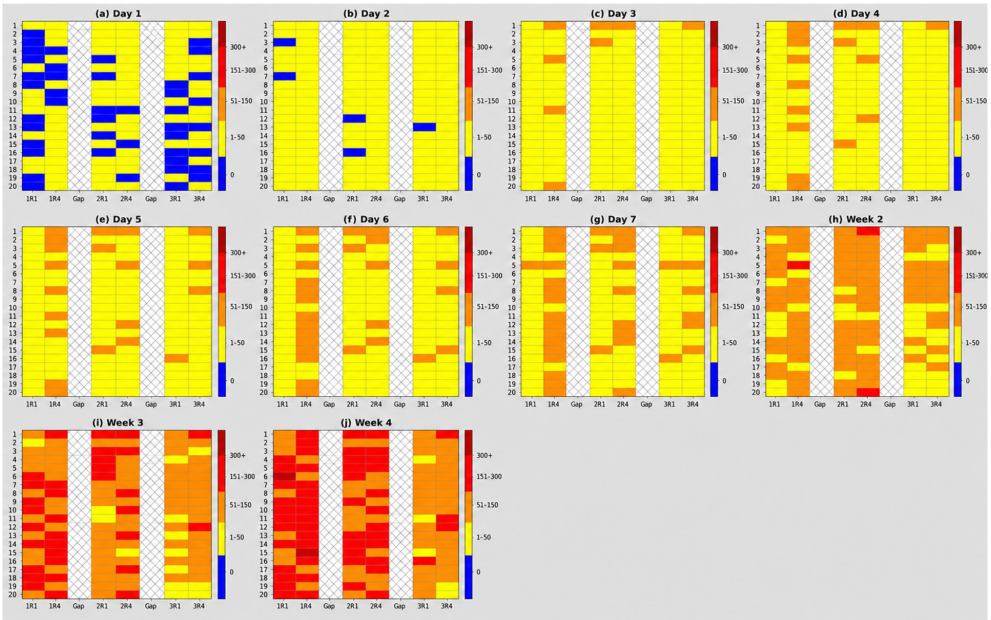

Figure 9. Spatial–temporal distribution of *Frankliniella occidentalis* at Homme Farm, EC Drummond, Ross on Wye, UK. Heatmaps show adult *F. occidentalis* captured on blue sticky traps at EC Drummond, Ross on Wye, UK. Subplots (**a–j**) represent sampling at days 1–7 and weeks 2–4 following lure deployment. The *x*-axis indicates trap position by polytunnel and row (gaps between tunnels hatched), and the *y*-axis denotes relative position along rows. Cell colour represents thrips capture per trap using a discrete scale: 0 (blue), 1–50 (yellow), 51–150 (orange), 151–300 (red), and >300 (dark red). Hatched cells indicate non-sampled positions. Across sites, captures were typically highest at polytunnel entrances and became more spatially structured over time, with increasing abundance in later assessments.

Table 2. Total thrips catch 28 days post-treatment with realised combinations of attractants and dispersers.

Farm	Treatment	Log(Mean)	SE	Lwr 95%	Upr 95%
EC Drummond	None.None	4.265	0.123	4.024	4.506
	Pani.Blister Pack	5.022	0.121	4.785	5.260
	Verbenone.Blister Pack	4.585	0.122	4.346	4.824
	Blend.Blister Pack	5.061	0.123	4.821	5.301
	Pani.Chewing Gum	5.067	0.121	4.829	5.304
	Verbenone.Chewing Gum	4.647	0.123	4.407	4.887
	Blend.Chewing Gum	5.350	0.120	5.115	5.586
	Lurem.Lurem	5.221	0.122	4.982	5.459
Goose Farm	None.None	4.640	0.101	4.442	4.838
	Pani.Blister Pack	5.203	0.099	5.009	5.396
	Verbenone.Blister Pack	5.010	0.101	4.813	5.207
	Blend.Blister Pack	5.247	0.100	5.050	5.443
	Pani.Chewing Gum	5.245	0.099	5.051	5.440
	Verbenone.Chewing Gum	5.113	0.101	4.915	5.310
	Blend.Chewing Gum	5.482	0.099	5.287	5.676
	None.Tube	4.627	0.101	4.429	4.824
	Pani.Tube	5.232	0.099	5.039	5.426
	Verbenone.Tube	5.026	0.103	4.824	5.228
	Blend.Tube	5.558	0.100	5.362	5.753
	Lurem.Lurem	5.439	0.099	5.244	5.634
Homefield Farm	None.Empty Tube	1.600	0.492	0.635	2.565
	None.None	1.582	0.156	1.275	1.888
	Pani.Blister Pack	2.052	0.142	1.773	2.330
	Verbenone.Blister Pack	2.016	0.139	1.744	2.289
	Blend.Blister Pack	2.546	0.130	2.291	2.800
	None.Tube	1.611	0.162	1.294	1.928
	Pani.Tube	2.124	0.138	1.854	2.394
	Verbenone.Tube	1.946	0.145	1.661	2.231
	Blend.Tube	2.785	0.123	2.543	3.027
	Lurem.Lurem	2.379	0.135	2.115	2.644
Mockbeggar	None.None	3.797	0.109	3.583	4.012
	Pani.Blister Pack	4.292	0.108	4.081	4.503
	Verbenone.Blister Pack	4.104	0.109	3.891	4.318
	Blend.Blister Pack	4.679	0.109	4.465	4.893
	None.Tube	3.641	0.115	3.416	3.866
	Pani.Tube	4.516	0.106	4.308	4.724
	Verbenone.Tube	4.280	0.107	4.071	4.489
	Blend.Tube	4.867	0.106	4.659	5.076
	Lurem.Lurem	4.630	0.106	4.422	4.839

4. Discussion

Across the full sequence of experiments (2018–2021), this study demonstrates that *p*-anisaldehyde (PANI) and verbenone are effective field-active attractants for *Frankliniella occidentalis*, with their blended formulation providing the most consistent enhancement of sticky trap capture. Importantly, these findings extend beyond confirmation of individual attractant activity, instead demonstrating that blended plant-derived volatiles can provide sustained and context-dependent improvements in trap performance when coupled with appropriate release systems.

Although individual compounds were active across weeks worth of trials, their effects were less consistent across time, whereas the blend maintained elevated capture throughout all assessment periods. This supports the interpretation that WFT respond more strongly to combinations of plant-derived volatiles than to single compounds, consistent with previous studies showing attraction to a diverse range of floral and host-associated odours, including PANI, verbenone, linalool, geraniol, and eugenol [22,23]. One potential critique of the

use of floral odours as attractants relates to the level of competition of the VOCs with background noise. Although there may be competition between plant-derived attractants and the crop odour background, both field and behavioural studies have shown that thrips still respond effectively to these semiochemical cues under such situations [23,24,27]. Additionally, background plant odours have been shown to be modulators of, rather than eliminators of, thrips responses to semiochemical cues [26,66]. Plant-derived volatile lures may, therefore, be best viewed as enhancements to the existing local chemosphere rather than as ecologically novel introduced signals.

From 2019, work focused on enhancing the delivery and application of the blended compounds through dispenser technologies, with results clearly showing that this dispensation progression is a core requirement for effective trapping in fully commercial settings. There was clear temporal separation between treatment effects; during the initial seven days, cumulative thrips capture followed a similar power–law trajectory across all treatments, with no detectable differences among attractant–dispenser combinations. This suggests that early capture is either stochastic or dominated by background population dynamics and initial dispersal behaviour rather than strong discrimination between semiochemical cues. Over the longer-term trials, the clear differences between treatments, dominated by the performance of blended components and Lurem-TR over single-compound applications, show that the advantages of particular lure systems may only become apparent over longer deployment periods; this should, therefore, be a core consideration for future trials aiming to validate the applied potential of new compounds. Above all, the improved performance of blended attractants over time is consistent with the broader understanding of insect olfactory ecology. WFT encounter complex mixtures of plant volatiles during host location, and responses to single compounds may, therefore, be weaker or less persistent than responses to more representative odour blends. Multi-component cues can activate multiple olfactory pathways simultaneously, enhancing signal strength and potentially behavioural response [67,68]. In the present study, the blend consistently ranked among the highest-performing treatments at later time points, despite containing equivalent total volumes of active ingredients as single-compound treatments. This supports the idea that odour composition, rather than simply dose, is a key determinant of efficacy.

The importance of dispenser technology in determining realised field performance was clear throughout the multi-year development. The initial introduction of EVA tube dispensers represented an important transition from simple cellulose-based carrier systems to a greater level of control in the VOC release, addressing the practical limitations of rapidly depleting delivery systems [54,69], while the inclusion of extruded polymers and blister packs in 2021 further strengthened the conclusion that dispensation must be a core consideration in the future development and field validation of semiochemical compounds. While early-phase responses were similar across treatments, divergence at later time points suggests that sustained emission profiles became increasingly important. Dispenser materials, such as EVA tubing and polymer matrices, are known to influence release kinetics and longevity [46,47]. Likewise, the stronger cumulative performance observed for certain blend–dispenser combinations, particularly in tube and chewing gum formats, indicates that these systems were able to maintain attractive emission rates over extended periods compared to basal preparation. This aligns with the general requirement for semiochemical dispensers to balance release rate and longevity to remain within biologically effective thresholds [42,45].

Site-specific variation was evident across the 2021 trials and represents an important component of the overall findings. Homefield Farm consistently exhibited lower thrips capture than the other sites, primarily due to its inclusion as an early-season trial to assess for sensitivity. Only the blend and Lurem-TR showed clear separation from the

control at day 28, showcasing the sensitivity of the blend over singular components at low pest pressures. Importantly, the relative ranking of treatments, particularly the strong performance of the blend, was maintained across sites where sufficient population pressure was present, suggesting that the observed effects are robust to environmental variability and have a high degree of utility at both low and high population thresholds. This may prove useful in guiding growers towards more effective targeting of insecticides; by spraying during early infestation, pest pressure may be dramatically reduced before a population explosion or high disease abundance occurs [2,70].

Spatial analyses across the study further support the interpretation that lure effects were not artefacts of trap placement. While earlier trials identified spatial structuring in trap capture and suggested movement of thrips towards newly introduced odours, the 2021 data showed consistent accumulation patterns across rows, tunnels, and replicates, with no strong evidence of systematic positional bias. This indicates that the observed treatment effects are attributable to behavioural responses rather than spatial confounding, although local airflow and tunnel structure may still contribute to fine-scale variation, particularly with regard to the initial ingress of the thrips at the beginning of the season and before full establishment. As a result, agricultural stakeholders can leverage their trapping against the backdrop of the dynamic movements of WFT. In this instance, placement of trap crops or sticky traps is clearly best when near the outer extremities of the polytunnel systems during the early season. In doing so, greater targeting and efficiency may be gained, and with them a reduction in the investment required for traps and lures on long term bases. Such advances should not, of course, be limited to the semiochemicals used. It is now known that the colours of the traps themselves can be optimised [17]. By introducing commercially standardised traps with optimised colours or patterns, trap capture may be enhanced again, further increasing the sensitivity of detection thresholds. Ultimately, the aim of low-pest pressure monitoring would be to detect WFT ingress as early as possible, using it as a trigger for increased system-wide monitoring and as a mechanism to optimise the timing for future interventions such as insecticide application.

Overall, these results demonstrate that both attractant composition and dispenser design are critical determinants of field performance. The PANI–verbenone blend emerged as the most effective formulation across all stages of the study and demonstrated that blended floral components can significantly improve performance over single compounds even when the input is halved. Furthermore, the transition from simple cellulose carriers to controlled-release polymer systems improved performance over longer deployment periods, addressing a key concern for application requirements. Importantly, these trials show that such systems can perform comparably to a commercial standard under realistic agricultural conditions. Future optimisation should, therefore, focus on enhancing the blended VOC input to actively compete in the background chemosphere, refining release kinetics and deployability, extending field longevity, and evaluating performance under low population densities where improvements in monitoring sensitivity are likely to have the greatest practical impact.

Author Contributions: Conceptualisation, M.J.W., A.E.D., F.S., Z.S. and T.M.B.; methodology, M.J.W., A.E.D., J.C.B., F.S., O.J., J.S., B.J.C., Z.S. and T.M.B.; software, M.J.W., A.E.D. and J.C.B.; validation, M.J.W., A.E.D., J.C.B., F.S. and T.M.B.; formal analysis, A.E.D. and J.C.B.; investigation, M.J.W., A.E.D., F.S., O.J., R.S.T. and H.F.; resources, F.S., O.J., J.S., E.J.L. and T.M.B.; data curation, M.J.W., A.E.D. and J.C.B.; writing—original draft, M.J.W., A.E.D., J.C.B., F.S. and T.M.B.; writing—review and editing, M.J.W., A.E.D., J.C.B., F.S., O.J., R.S.T., H.F., J.S., B.J.C., Z.S., E.J.L. and T.M.B.; visualization, M.J.W., A.E.D. and T.M.B.; supervision, F.S., O.J., E.J.L. and T.M.B.; project administration, F.S. & T.M.B.; funding acquisition, F.S., O.J. and T.M.B. All authors have read and agreed to the published version of the manuscript.

Funding: The 2018 and 2019 field trials and associated works were funded by the Knowledge Economy Skills Scholarships 2 (KESS 2) initiative and were partly funded by the Welsh Government's European Social Fund (ESF) convergence program for West Wales and the Valleys with industry support from Agrisense Ltd. and Lisk & Jones Ltd. alongside Natural Products Biohub Centre, funded via UK Research and Innovation funding from the 'Building a Green Future' strategic theme (project number: UKRI239). The 2021 field trials and associated works were funded by Innovate UK funding coupled with industry support from Razbio Ltd. (project number: 86740), with additional technical support provided by Lisk & Jones Ltd.

Data Availability Statement: All data files are available from the figshare database (https://doi.org/10.6084/m9.figshare.32404485).

Acknowledgments: Field trial sites and regular assistance were provided by N. I. Cockburn Ltd., W. C. Chambers Ltd., and E. C. Drummond Ltd. We would particularly like to thank Rupert Carter, Salih Hodzhov, Javi Caceres, Richard Hibbard, and Neil Cockburn for their assistance in setting up and facilitating all field trials. We would also like to thank Razbio Ltd., Koppert BV, and Russell IPM Ltd. for providing the EVA tube and extruded polymer, Lurem TR, and blister pack dispensers, respectively. Likewise, we would like to thank Laura Quinones for her contributions to some of the preparations for the 2018 field trial.

Conflicts of Interest: The respective authors have received research funds as follows. Martyn Wood was funded via Innovate UK funding (project number 86740), inclusive of partial industry match-funded support from Razbio Ltd., to conduct the 2021 trials. Alexander Dearden was funded by the Knowledge Economy Skills Scholarships 2 (KESS 2) initiative, partly funded by the Welsh Government's European Social Fund (ESF) convergence program for West Wales and the Valleys with industry support from Agrisense Ltd. for the 2018 and 2019 trials, while Lisk & Jones Consultancy Ltd. also provided technical support and materials preparation for the trials via partnership with the Knowledge Economy Skills Scholarships 2 (KESS 2) initiative, partly funded by the Welsh Government's European Social Fund (ESF) convergence program for West Wales and the Valleys. Tariq Butt was supported through UK Research and Innovation funding from the 'Building a Green Future' strategic theme (project number UKRI239). No other authors received funding to support their contributions to this body of work. Farooq Shah is the CEO of Razbio Ltd., Owen Jones is a partner in Lisk & Jones Consultancy Ltd. and provided technical support and input in-kind, while John Stobart also provided in-kind technical support as an independent contractor. Lisk & Jones Consultancy Ltd. has no claim of ownership over the lures developed by Razbio Ltd.; therefore, the authors declare that there are no conflicts of interest between any of the authors or the companies therein.

References

1. Mouden, S.; Sarmiento, K.F.; Klinkhamer, P.G.L.; Leiss, K.A. Integrated Pest Management in Western Flower Thrips: Past, Present and Future. *Pest Manag. Sci.* **2017**, *73*, 813–822. [CrossRef]
2. Reitz, S.R.; Gao, Y.; Kirk, W.D.J.; Hoddle, M.S.; Leiss, K.A.; Funderburk, J.E. Invasion Biology, Ecology, and Management of Western Flower Thrips. *Annu. Rev. Entomol.* **2020**, *65*, 17–37. [CrossRef]
3. Mukherjee, T.; Sharma, L.K.; Thakur, M.; Banerjee, D.; Chandra, K. Whether Curse or Blessing: A Counterintuitive Perspective on Global Pest Thrips Infestation under Climatic Change with Implications to Agricultural Economics. *Sci. Total Environ.* **2023**, *867*, 161349. [CrossRef]
4. Chiapello, M.; Bosco, L.; Ciuffo, M.; Ottati, S.; Salem, N.; Rosa, C.; Tavella, L.; Turina, M. Complexity and Local Specifi City of the Virome Associated with Tospovirus-Transmitting Thrips Species. *J. Virol.* **2021**, *95*, e0059721. [CrossRef] [PubMed]
5. Szostek, S.A.; Rodriguez, P.; Sanchez, J.; Adkins, S.; Naidu, R.A. Western Flower Thrips Can Transmit Tomato Spotted Wilt Virus from Virus-Infected Tomato Fruits. *Plant Health Prog.* **2017**, *18*, 1–6. [CrossRef]
6. Chinnaiah, S.; Gautam, S.; Herron, B.; Workneh, F.; Rush, C.M.; Gadhave, K.R. Novel Strains of a Pandemic Plant Virus, Tomato Spotted Wilt Orthotospovirus, Increase Vector Fitness and Modulate Virus Transmission in a Resistant Host. *Front. Microbiol.* **2023**, *14*, 1257724. [CrossRef] [PubMed]
7. Kirk, W.D.J.; Terry, L.I. The Spread of the Western Flower Thrips *Frankliniella occidentalis* (Pergande). *Agric. For. Èntomol.* **2003**, *5*, 301–310. [CrossRef]
8. Gao, Y.; Reitz, S.R. Western Flower Thrips Resistance to Insecticides: Detection, Mechanisms and Management Strategies. *Pest Manag. Sci.* **2012**, *68*, 1111–1121. [CrossRef]

9. Zhang, K.; Yuan, J.; Wang, J.; Hua, D.; Zheng, X.; Tao, M.; Zhang, Z.; Wan, Y.; Wang, S.; Zhang, Y.; et al. Susceptibility Levels of Field Populations of *Frankliniella occidentalis* (Thysanoptera: Thripidae) to Seven Insecticides in China. *Crop Prot.* **2022**, *153*, 105886. [CrossRef]
10. Li, D.-G.; Shang, X.-Y.; Reitz, S.; Nauen, R.; Lei, Z.-R.; Lee, S.H.; Gao, Y.-L. Field Resistance to Spinosad in Western Flower Thrips *Frankliniella occidentalis* (Thysanoptera: Thripidae). *J. Integr. Agric.* **2016**, *15*, 2803. [CrossRef]
11. Bielza, P.; Quinto, V.; Contreras, J.; Torné, M.; Martín, A.; Espinosa, P.J. Resistance to Spinosad in the Western Flower Thrips, *Frankliniella occidentalis* (Pergande), in Greenhouses of South-Eastern Spain. *Pest Manag. Sci.* **2007**, *63*, 682–687. [CrossRef]
12. Muvea, A.M.; Waiganjo, M.M.; Kutima, H.L.; Osiemo, Z.; Nyasani, J.O.; Subramanian, S. Attraction of Pest Thrips (Thysanoptera: Thripidae) Infesting French Beans to Coloured Sticky Traps with Lurem-TR and Its Utility for Monitoring Thrips Populations. *Int. J. Trop. Insect Sci.* **2014**, *34*, 197–206. [CrossRef]
13. Pobozniak, M.; Tokarz, K.; Musynov, K. Evaluation of Sticky Trap Colour for Thrips (Thysanoptera) Monitoring in Pea Crops (*Pisum sativum* L.). *J. Plant Dis. Prot.* **2020**, *127*, 307–321. [CrossRef]
14. Broughton, S.; Harrison, J. Evaluation of Monitoring Methods for Thrips and the Effect of Trap Colour and Semiochemicals on Sticky Trap Capture of Thrips (Thysanoptera) and Beneficial Insects (Syrphidae, Hemerobiidae) in Deciduous Fruit Trees in Western Australia. *Crop Prot.* **2012**, *42*, 156–163. [CrossRef]
15. Broughton, S.; Cousins, D.A.; Rahman, T. Evaluation of Semiochemicals for Their Potential Application in Mass Trapping of *Frankliniella occidentalis* (Pergande) in Roses. *Crop Prot.* **2015**, *67*, 130–135. [CrossRef]
16. Otieno, J.A.; Stukenberg, N.; Weller, J.; Poehling, H.M. Efficacy of LED-Enhanced Blue Sticky Traps Combined with the Synthetic Lure Lurem-TR for Trapping of Western Flower Thrips (*Frankliniella occidentalis*). *J. Pest Sci.* **2018**, *91*, 1301–1314. [CrossRef]
17. Dearden, A.E.; Wood, M.J.; Frend, H.O.; Butt, T.M.; Allen, W.L. Visual Modelling Can Optimise the Appearance and Capture Efficiency of Sticky Traps Used to Manage Insect Pests. *J. Pest Sci.* **2024**, *97*, 469–479. [CrossRef]
18. Sampson, C.; Kirk, W.D.J. Can Mass Trapping Reduce Thrips Damage and Is It Economically Viable? Management of the Western Flower Thrips in Strawberry. *PLoS ONE* **2013**, *8*, e80787. [CrossRef]
19. Teulon, D.A.J.; Davidson, M.M.; Perry, N.B.; Nielsen, M.C.; Castañé, C.; Bosch, D.; Riudavets, J.; Van Tol, R.W.H.M.; De Kogel, W.J. Methyl Isonicotinate—A Non-Pheromone Thrips Semiochemical—And Its Potential for Pest Management. *Int. J. Trop. Insect Sci.* **2017**, *37*, 50–56. [CrossRef]
20. Avellaneda, J.; Díaz, M.; Coy-Barrera, E.; Rodríguez, D.; Osorio, C. Rose Volatile Compounds Allow the Design of New Control Strategies for the Western Flower Thrips (*Frankliniella occidentalis*). *J. Pest Sci.* **2021**, *94*, 129–142. [CrossRef]
21. Koschier, E.H. Essential Oil Compounds for Thrips Control—A Review. *Nat. Prod. Commun.* **2008**, *3*, 1171–1182. [CrossRef]
22. Koschier, E.H.; De Kogel, W.J.; Visser, J.H. Assessing the Attractiveness of Volatile Plant Compounds to Western Flower Thrips *Frankliniella occidentalis*. *J. Chem. Ecol.* **2000**, *26*, 2643–2655. [CrossRef]
23. Abdullah, Z.S.; Greenfield, B.P.; Ficken, K.J.; Taylor, J.W.; Wood, M.; Butt, T.M. A New Attractant for Monitoring Western Flower Thrips, *Frankliniella occidentalis* in Protected Crops. *Springerplus* **2015**, *4*, 89. [CrossRef]
24. Zafar, Z.; Wood, M.J.; Fatima, S.; Bhatti, M.F.; Shah, F.A.; Saud, Z.; Loveridge, E.J.; Karaca, I.; Butt, T.M. Identification of the Odorant Binding Proteins of Western Flower Thrips (*Frankliniella occidentalis*), Characterization and Binding Analysis of FoccOBP3 with Molecular Modelling, Molecular Dynamics Simulations and a Confirmatory Field Trial Identificati. *J. Biomol. Struct. Dyn.* **2025**, *43*, 6853–6868. [CrossRef]
25. Teulon, D.A.J.; Davidson, M.M.; Hedderley, D.I.; James, D.E.; Fletcher, C.D.; Larsen, L.; Green, V.C.; Perry, N.B. 4-Pyridyl Carbonyl and Related Compounds as Thrips Lures: Effectiveness for Onion Thrips and New Zealand Flower Thrips in Field Experiments. *J. Agric. Food Chem.* **2007**, *55*, 6198–6205. [CrossRef]
26. Teulon, D.A.J.; Davidson, M.M.; Nielsen, M.; Butler, R.; Bosch, D.; Riudavets, J.; Castañé, C. Efficacy of a Non-Pheromone Semiochemical for Trapping of Western Flower Thrips in the Presence of Competing Plant Volatiles in a Nectarine Orchard. *Span. J. Agric. Res.* **2018**, *16*, e10SC0. [CrossRef]
27. Abdullah, Z.S.; Ficken, K.J.; Greenfield, B.P.J.; Butt, T.M. Innate Responses to Putative Ancestral Hosts: Is the Attraction of Western Flower Thrips to Pine Pollen a Result of Relict Olfactory Receptors? *J. Chem. Ecol.* **2014**, *40*, 534–540. [CrossRef] [PubMed]
28. Ravid, U.; Putievsky, E.; Katzir, I.; Lewinsohn, E.; Dudai, N. Identification of (1R)(+)-Verbenone in Essential Oils of *Rosmarinus officinalis* L. *Flavour Fragr. J.* **1997**, *12*, 1995–1998. [CrossRef]
29. Marzoug, H.N.B.; Romdhane, M.; Lebrihi, A.; Lebrihi, F.; Couderc, F.; Abderraba, M.; Abderraba, M.L.; Bouajila, J. Eucalyptus Oleosa Essential Oils: Chemical Composition and Antimicrobial and Antioxidant Activities of the Oils from Different Plant Parts (Stems, Leaves, Flowers and Fruits). *Molecules* **2011**, *16*, 1695–1709. [CrossRef]
30. Abdullah, Z.S.; Butt, T.M. Preferences of the Peripheral Olfactory System of Western Flower Thrips, *Frankliniella occidentalis* towards Stereoisomers of Common Plant Volatiles. *Chemoecology* **2014**, *25*, 47–51. [CrossRef]
31. Berger, R.G.; Zorn, H. Flavors and Fragrances. In *Advances in Fungal Biotechnology for Industry, Agriculture, and Medicine*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 341–358. [CrossRef]

32. Davis, T.S.; Crippen, T.L.; Hofstetter, R.W.; Tomberlin, J.K. Microbial Volatile Emissions as Insect Semiochemicals. *J. Chem. Ecol.* **2013**, *39*, 840–859. [CrossRef]
33. Kandasamy, D.; Gershenzon, J.; Hammerbacher, A. Volatile Organic Compounds Emitted by Fungal Associates of Conifer Bark Beetles and Their Potential in Bark Beetle Control. *J. Chem. Ecol.* **2016**, *42*, 952–969. [CrossRef]
34. Hunt, D.W.A.; Borden, J.H. Conversion of Verbenols to Verbenone by Yeasts Isolated from *Dendroctonus ponderosae* (Coleoptera: Scolytidae). *J. Chem. Ecol.* **1990**, *16*, 1385–1397. [CrossRef]
35. De Simón, B.F.; Esteruelas, E.; Muñoz, À.M.; Cadahía, E.; Sanz, M. Volatile Compounds in Acacia, Chestnut, Cherry, Ash, and Oak Woods, with a View to Their Use in Cooperage. *J. Agric. Food Chem.* **2009**, *57*, 3217–3227. [CrossRef]
36. Kundu, A.; Mitra, A. Methoxybenzaldehydes in Plants: Insight to the Natural Resources, Isolation, Application and Biosynthesis. *Curr. Sci.* **2016**, *111*, 1325–1334. [CrossRef]
37. Guyot, C.; Scheirman, V.; Collin, S. Floral Origin Markers of Heather Honeys: *Calluna vulgaris* and *Erica arborea*. *Food Chem.* **1999**, *64*, 3–11. [CrossRef]
38. De Jager, L.S.; Perfetti, G.A.; Diachenko, G.W. Comparison of Headspace-SPME-GC-MS and LC-MS for the Detection and Quantification of Coumarin, Vanillin, and Ethyl Vanillin in Vanilla Extract Products. *Food Chem.* **2008**, *107*, 1701–1709. [CrossRef]
39. Pattrick, J.G.; Shepherd, T.; Hoppitt, W.; Plowman, N.S.; Willmer, P. A Dual Function for 4-Methoxybenzaldehyde in *Petasites fragrans*? Pollinator-Attractant and Ant-Repellent. *Arthropod Plant Interact.* **2017**, *11*, 623–627. [CrossRef]
40. Kirk, W.D.J. Effect of Some Floral Scents on Host Finding by Thrips (Insecta: Thysanoptera). *J. Chem. Ecol.* **1985**, *11*, 35–43. [CrossRef]
41. Teulon, D.A.J.; Penman, D.R.; Ramakers, P.M.J. Volatile Chemicals for Thrips (Thysanoptera: Thripidae) Host Finding and Applications for Thrips Pest Management. *J. Econ. Entomol.* **1993**, *86*, 1405–1415. [CrossRef]
42. Byers, J.A. Active Space of Pheromone Plume and Its Relationship to Effective Attraction Radius in Applied Models. *J. Chem. Ecol.* **2008**, *34*, 1134–1145. [CrossRef]
43. Nielsen, M.C.; Sansom, C.E.; Larsen, L.; Worner, S.P.; Rostás, M.; Chapman, R.B.; Butler, R.C.; de Kogel, W.J.; Davidson, M.M.; Perry, N.B.; et al. Volatile Compounds as Insect Lures: Factors Affecting Release from Passive Dispenser Systems. *N. Z. J. Crop Hortic. Sci.* **2019**, *47*, 208–223. [CrossRef]
44. Zhang, A.; Leskey, T.C.; Bergh, J.C.; Walgenbach, J.F. Sex Pheromone Dispenser Type and Trap Design Affect Capture of Dogwood Borer. *J. Chem. Ecol.* **2013**, *39*, 390–397. [CrossRef] [PubMed]
45. Stelinski, L.L.; Il'Ichev, A.L.; Gut, L.J. Efficacy and Release Rate of Reservoir Pheromone Dispensers for Simultaneous Mating Disruption of Codling Moth and Oriental Fruit Moth (Lepidoptera: Tortricidae). *J. Econ. Entomol.* **2009**, *102*, 315–323. [CrossRef]
46. Atterholt, C.A.; Delwiche, M.J.; Rice, R.E.; Krochta, J.M. Controlled Release of Insect Sex Pheromones from Paraffin Wax and Emulsions. *J. Control. Release* **1999**, *57*, 233–247. [CrossRef]
47. Tomaszewska, E.; Hebert, V.R.; Brunner, J.F.; Jones, V.P.; Doerr, M.; Hilton, R. Evaluation of Pheromone Release from Commercial Mating Disruption Dispensers. *J. Agric. Food Chem.* **2005**, *53*, 2399–2405. [CrossRef]
48. McDonough, L.M.; Aller, W.C.; Knight, A.L. Performance Characteristics of a Commercial Controlled-Release Dispenser of (*Cydia pomonella*) by Mating Disruption. *J. Chem. Ecol.* **1992**, *18*, 2177–2189. [CrossRef]
49. Gavara, A.; Navarro-Llopis, V.; Primo, J.; Vacas, S. Influence of Weather Conditions on *Lobesia botrana* (Lepidoptera: Tortricidae) Mating Disruption Dispensers' Emission Rates and Efficacy. *Crop Prot.* **2022**, *155*, 105926. [CrossRef]
50. Corbetta, M.; Bricchi, L.; Rossi, V.; Fedele, G. The Dynamics of Pheromone Release in Two Passive Dispensers Commonly Used for Mating Disruption in the Control of Lobesia Botrana and Eupoecilia Ambiguella in Vineyards. *Insects* **2024**, *15*, 962. [CrossRef] [PubMed]
51. Stelinski, L.; Holdcraft, R.; Rodriguez-Saona, C. Female Moth Calling and Flight Behavior Are Altered Hours Following Pheromone Autodetection: Possible Implications for Practical Management with Mating Disruption. *Insects* **2014**, *5*, 459–473. [CrossRef]
52. Shelly, T.E.; Pahio, E.; Edu, J. Synergistic and Inhibitory Interactions between Methyl Eugenol and Cue Lure Influence Trap Catch of Male Fruit Flies, *Bactrocera dorsalis* (Hendel) and *B. Cucurbitae* (Diptera: Tephritidae). *Fla. Entomol.* **2004**, *87*, 481–486. [CrossRef]
53. Stockton, D.G.; Cha, D.H.; Loeb, G.M. Does Habituation Affect the Efficacy of Semiochemical Oviposition Repellents Developed Against *Drosophila suzukii*? *Environ. Entomol.* **2021**, *50*, 1322–1331. [CrossRef]
54. El-Sayed, A.M.; Suckling, D.M.; Wearing, C.H.; Byers, J.A. Potential of Mass Trapping for Long-Term Pest Management and Eradication of Invasive Species. *J. Econ. Entomol.* **2006**, *99*, 1550–1564. [CrossRef]
55. van Tol, R.W.H.M.; de Bruin, A.; Butler, R.C.; Davidson, M.M.; Teulon, D.A.J.; de Kogel, W.J. Methyl Isonicotinate Induces Increased Walking and Take-off Behaviour in Western Flower Thrips, *Frankliniella occidentalis*. *Entomol. Exp. Appl.* **2012**, *142*, 181–190. [CrossRef]
56. Bivand, R.; Nowosad, J.; Lovelace, R. *SpData: Datasets for Spatial Analysis*; R Foundation for Statistical Computing: Vienna, Austria, 2026.
57. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2025. Available online: https://www.r-project.org/ (accessed on 19 May 2026).

58. Brooks, M.E.; Kristensen, K.; van Benthem, K.J.; Magnusson, A.; Berg, C.W.; Nielsen, A.; Skaug, H.J.; Mächler, M.; Bolker, B.M. GlmmTMB Balances Speed and Flexibility among Packages for Zero-Inflated Generalized Linear Mixed Modeling. *R J.* **2017**, *9*, 378–400. [CrossRef]
59. Wickham, H.; François, R.; Henry, L.; Müller, K.; Vaughan, D. *Dplyr: A Grammar of Data Manipulation*; Posit: Boston, MA, USA, 2026.
60. Lenth, R.; Piaskowski, J. Emmeans: Estimated Marginal Means, Aka Least-Squares Means. *Am. Stat.* **2026**, *34*, 216–221.
61. Gohel, D.; Skintzos, P. *Flextable: Functions for Tabular Reporting*; ArData: Puteaux, France, 2026.
62. Wickham, H. *Elegant Graphics for Data Analysis*, 3rd ed.; Springer: New York, NY, USA, 2016.
63. Gohel, D.; Moog, S.; Heckmann, M. *Officer: Manipulation of Microsoft Word and PowerPoint Documents*; ArData: Puteaux, France, 2026.
64. Wickham, H.; Pedersen, T.; Seidel, D. *Scales: Scale Functions for Visualization*; Posit: Boston, MA, USA, 2025.
65. Pebesma, E.; Bivand, R. *Spatial Data Science: With Applications in R. Chapman and Hall/CRC*; Chapman and Hall/CRC: Boca Raton, FL, USA, 2023.
66. Koschier, E.H.; Nielsen, M.C.; Spangl, B.; Davidson, M.M.; Teulon, D.A.J. The Effect of Background Plant Odours on the Behavioural Responses of *Frankliniella occidentalis* to Attractive or Repellent Compounds in a Y-Tube Olfactometer. *Entomol. Exp. Appl.* **2017**, *163*, 160–169. [CrossRef]
67. Riffell, J.A.; Shlizerman, E.; Sanders, E.; Abrell, L.; Medina, B.; Hinterwirth, A.J.; Kutz, J.N. Flower Discrimination by Pollinators in a Dynamic Chemical Environment. *Science* **2014**, *344*, 1515–1518. [CrossRef]
68. Conchou, L.; Lucas, P.; Meslin, C.; Proffit, M.; Staudt, M.; Renou, M. Insect Odorscapes: From Plant Volatiles to Natural Olfactory Scenes. *Front. Physiol.* **2019**, *10*, 972. [CrossRef]
69. Morrison, W.R.; Scully, E.D.; Campbell, J.F. Towards Developing Areawide Semiochemical-Mediated, Behaviorally-Based Integrated Pest Management Programs for Stored Product Insects. *Pest Manag. Sci.* **2021**, *77*, 2667–2682. [CrossRef]
70. Shipp, J.L.; Wang, K.; Binns, M.R. Economic Injury Levels for Western Flower Thrips (Thysanoptera: Thripidae) on Greenhouse Cucumber. *J. Econ. Entomol.* **2000**, *93*, 1732–1740. [CrossRef]