

From functional traits to community dynamics in parasitoid wasps

Scientific background

Agricultural expansion impairs insect-delivered ecosystem services: Agriculture, the most widespread form of land use, takes up more than one-third of the global landmass and is increasingly impacting natural ecosystems (Wanger *et al.*, 2020). The abundance, species richness and functional diversity of many plants, animals and microbes are lower on farmlands than in natural habitats, especially in monocultures with high inputs of agrochemicals (Lichtenberg *et al.*, 2017). Intensive farming practices also disrupt the delivery of several ecosystem services, generating harmful impacts such as reduced soil, water and air quality.

Insects play key roles in agroecosystems, both negative (as herbivores and disease vectors of crops) and positive (as providers of pollination and pest control services). The abundance and diversity of beneficial insects are inversely related to the proportion of agricultural habitat in the landscape (Chaplin-Kramer *et al.* 2011, Kennedy *et al.*, 2013). High species richness of beneficial insects improves agricultural pollination, pest control and the resulting crop yields (Dainese *et al.*, 2019). Nevertheless, a large recent synthesis found that increased areas of natural habitat around fields do not consistently reduce pest populations and their damage to crops (Karp *et al.*, 2018). Namely, in some locations and crops, local (e.g., Rusch *et al.*, 2016) and introduced (e.g., Grab *et al.*, 2018) natural enemies are less abundant and effective in farm-dominated areas than in fields surrounded by natural habitat. Yet in other locations and production systems, this effect is absent or even reversed (e.g., Lantero *et al.*, 2019). Furthermore, at smaller spatial scales, some natural enemies within agroecosystems concentrate their activity in natural and semi-natural patches (such as flowering strips along field borders), rather than within the fields. This restricts their pest control services to non-crop habitats, even if they are abundant in the large-scale agricultural landscape (Derocles *et al.*, 2014, Feng *et al.*, 2017, preliminary results Fig. 1).

The apparent disconnect between the abundance and richness of natural enemies and their pest control services may be resolved by understanding how local farm management interacts with their life-history traits (Karp *et al.*, 2018). This is, in fact, a main aim of this proposal.

Intensive farming shapes insect communities through trait filtering: Intensively managed fields are ploughed, fertilized, sprayed, trimmed and harvested – all of which are potential sources of disturbance to resident insects. They are also often poor in some essential resources for beneficial insects, such as floral nectar for natural enemies (preliminary results, Fig.

2) or nesting sites for bees (Williams *et al.*, 2010). Such stressors are viewed as ecological filters, which allow only a subset of species to establish and thrive in the fields.

Functional traits are increasingly used to understand how ecological communities assemble and work (Moretti *et al.*, 2017). This approach, profitably developed by plant community ecologists, has already been applied to some insect communities, and generated initial insights regarding traits that allow insects to cope with agricultural disturbances (Vandewalle *et al.*, 2010, Perović *et al.*, 2018). Insect species with high fecundity and long activity seasons are less prone to extinction in agricultural plots than low-fecundity and short-season species, presumably because they can better recover from disturbances. Likewise, species with generalist diets and high mobility are more likely to persist in agroecosystems than low-dispersing specialists, as they are able to use alternative food sources and habitats when the fields are disturbed. Finally, large-bodied insects are more sensitive to in-field agricultural intensification than small-bodied insects. This may result from food shortages in the agricultural habitats that limit growth (Oliveira *et al.*, 2016), or for selection for small, quickly-developing individuals in the often-disturbed farm habitats (Neff, 2020). These predictions, or subsets of them, were supported in studies that compared species composition and functional traits along gradients of agricultural intensification. The taxa tested so far include pollinators (Rader *et al.*, 2014), ground beetles (Hanson *et al.*, 2016), spiders (Hanson *et al.*, 2017), herbivorous hemipterans (Neff *et al.*, 2020) and other insect pests (Tamburini *et al.*, 2020). I propose to extend the functional trait perspective to communities of parasitoid wasps, important natural enemies of agricultural pests.

Trait measurements in insect community ecology have so far targeted mainly inter-specific variation, with a single mean trait value often assigned per species. Yet, it is also important to acknowledge and measure intra-specific trait variation (Moretti *et al.*, 2017, Perović *et al.*, 2018). Such variation can allow some phenotypes within a species to be locally adapted to crop habitats, while other phenotypes are better adapted to natural habitats. For example, female bees within 18 species in the Netherlands shrank in body size by 0.5-6.5% over a 147-year period (Oliveira *et al.*, 2016). A possible reason for this trend is increasing agricultural intensification that limited the bees' food resources, indicating that the smaller individuals within a species are better adapted to agriculture-dominated landscapes. Similarly, several morphological traits, such as wing loading and abdomen size, varied intra-specifically in dung beetles that originated from differentially disturbed forests (Raine *et al.*, 2018).

Agricultural management impacts parasitoids, important pest control agents:

Parasitoids are insects (wasps and flies) that lay their eggs in or on other arthropods (hosts). The

parasitoids' larvae feed on the hosts and eventually kill them. Adults are free-living, but sugar meals dramatically prolong adult longevity and fecundity in many species (Heimpel *et al.*, 1997, Tylianakis *et al.*, 2004). Parasitoids are speciose (>100,000 species worldwide) and effective natural enemies of crop pests, hence play key roles in biological control programs. Yet, they sometimes fail to establish and to suppress their hosts. Lack of resources, such as sugar or shelter, for the parasitoids' adult stage, is a common reason for such failures (Fiedler *et al.*, 2008; Begg *et al.*, 2016).

Parasitoids are diverse (>200 species) and ubiquitous (>10% of all vegetation-dwelling arthropods) in Israel's pomegranate and vineyard agroecosystems, which our lab team has studied over several years. In both crops, parasitoids mostly occur in natural habitats near the fields. Within the plots, they are more abundant in the green non-crop herbaceous vegetation than on the crop plants (Segoli *et al.*, 2020, Shapira *et al.*, 2018). In wine-producing vineyards, the focal crop of this proposal, the parasitoid species assemblage differs between the natural habitat and the crop plots. This is partly because the two habitats differ in plant composition, and in the composition of insect herbivores that serve as the parasitoids' hosts. Accordingly, the type of weed management implemented within the vineyards also affects the abundance and composition of parasitoids (Möller *et al.*, submitted). The frequency of sugar feeding is lower in parasitoid communities sampled within vineyards than in neighboring natural phrygana habitat, indicating limited access to nectar-producing plants within the plots (Kishinevsky & Keasar, 2021, preliminary results Fig. 2). Finally, the 'soft' insecticide indoxacarb, used to control lepidopteran pests, transiently reduces the total abundance of parasitoids and differentially affects individual species (preliminary results Fig. 3). Thus, farming activities within conventional vineyards shape the resident parasitoid communities in our study system, but the traits affecting the parasitoid's responses, and the ensuing impacts on pest suppression, are unknown.

The knowledge gap – trait-based understanding of parasitoid community structure and function: Numerous studies from different parts of the world describe parasitoid communities from natural habitats and from diverse agricultural crops under intensive and extensive management (e.g., conventional vs. organic fields). These descriptions are mostly focused on species composition, with little attention paid to functional traits as adaptations for specific environments. Consequently, little is known about the suites of traits that shape assemblages of natural enemies of crop pests in agroecosystems, and about their functional significance (Perović *et al.*, 2018). Namely, which traits allow some parasitoids to thrive in some agroecosystems but not in others? And how do they affect their pest control efficiency and the

resulting crop yields? This knowledge gap limits our ability to guarantee successful establishment of natural enemies and effective pest suppression in biological control interventions.

At the intra-specific level, only a few studies characterized differences in life-history traits between parasitoid populations originating from different habitats. One of these studies hypothesized that parasitoids face a higher risk of egg limitation as host densities in their habitat increase, and respond by increased egg production. This hypothesis was supported in comparisons between *Anagrus daanei* parasitoids collected from host-poor natural habitats and conspecifics collected from host-rich vineyards (Segoli & Rosenheim, 2013). In another, *Venturia canescens* parasitoids from grain stores reproduced asexually and had higher initial egg loads than sexual females of the same species from natural habitats (Pelosse *et al.*, 2007). However, information about within-species variability in field populations and its significance for pest control is still lacking for most parasitoid species.

The methodological gap – Large-scale data acquisition capabilities: Insect ecology relies heavily on the visual identification of field-caught individuals. Several simple and cost-effective trapping techniques are available, such as malaise traps, sticky traps, pitfall traps and suction sampling. However, identifying and counting the trapped specimens is labor-intensive and requires taxonomical expertise. These constraints generate a technological gap that limits the scale of monitoring projects. A few recent projects combined insect trapping with machine learning methods to reduce the scouting workload required for monitoring crop pests (Nieuwenhuizen *et al.*, 2018; Zhong *et al.*, 2018; Liu *et al.* 2019; Chudzik *et al.*, 2020; Roosjen *et al.*, 2020). We recently developed our own software, based on deep learning, to identify an invasive forest pest (the psyllid *Glycaspis brimblecombei*) and its natural enemy (the parasitoid *Psyllaephagus bliteus*), caught on sticky traps. A few hundreds of scanned images of insects served as a training set. The resulted deep learning model discriminates the two focal organisms from one another, as well as from other elements such as leaves and other insects with > 90% accuracy (Keasar *et al.*, submitted, preliminary results Fig. 4). These image processing tasks are quite difficult as the insects are small (<5 mm) and stick to the traps in random poses (preliminary results Fig. 5). Here, we propose to train our software to identify and measure additional insects, to build an internet-based user interface for the software, and to develop a database for storing the sticky-trap images. These developments will address the need for large-scale monitoring of insect communities, both for the proposed project and for diverse future tasks in insect ecology and conservation.

Permanently and transiently unmanaged vineyards provide an ideal experimental setup for the proposed project: Low economic profitability occasionally pushes farmers to abandon their vineyards, that is to stop agrochemical inputs and harvesting for several years. Additionally, the Jewish religious practice of a ‘Sabbatical year’ (*Shmita*) mandates stopping all agricultural activities and harvesting in Israel every seventh year. The ancient rationale for the ‘Sabbatical year’ practice was “letting the land rest” (in lieu of crop rotation, not practiced in biblical times) and reducing social inequality. In modern Israel, the tradition is observed by several hundreds of religious farmers, is supported by government subsidies, and results in an independent set of vineyards that are transiently unmanaged. This practice generates a synchronized system of plots, which are set-aside for a year in each seven-year cycle, according to a fixed protocol, providing a unique setup for agroecological studies. Intriguingly, we are not aware of any previous study that investigated the effects of the ‘Sabbatical year’ practice on insects or on insect-delivered ecosystem services. By sampling vineyards that are either intensively managed, temporarily unmanaged during a ‘Sabbatical year’, or permanently abandoned, we will be able to compare parasitoid functional traits along a gradient of agricultural intensity.

Research objectives & expected significance

We aim to:

1. Understand the influence of agricultural in-field management intensity on the functional traits of local parasitoid communities.
2. Relate community-level functional trait distributions to crop pest control.
3. Expand the capabilities of our deep-learning software to perform automated measurements of parasitoid morphological traits, as a platform for future applications.
4. Assess the implications of the ‘Sabbatical year’, as a Traditional Ecological Knowledge practice, for conserving and restoring natural enemy assemblages.

The significance of our project is twofold:

- **Advancing trait-based understanding of natural enemy communities and biological control interactions:** Biological control has been outstandingly successful in many instances (e.g., Caltagirone & Doult, 1989, Pellissier *et al.*, 2017, Hoddle *et al.*, 1998, Wajnberg & Hassan, 1994). Nevertheless, such successes remain limited in number, undesirable side effects occasionally occur, and failures are often under-reported. While ecological theory provides established conceptual frameworks for understanding host-parasitoid interactions, they are still insufficiently integrated into current biological control practices in agriculture and conservation.

Indeed, biological control programs are still widely practiced as trial-and-error enterprises, rather than being guided by theory-driven principles (Wajnberg *et al.*, 2016; Mills, 2018). We will address important gaps in biological control theory by elucidating links between agricultural management, parasitoid life-history traits and pest control.

From an applied point of view, we will identify traits associated with successful parasitoid establishment in croplands. Such traits can then be incorporated into screening protocols for candidate biological control agents. At present, screening tests mainly for climate compatibility of the candidate species to their planned release sites, and for their host ranges (to assess invasion risks). It can be improved and refined by incorporating additional traits that our study will identify as important for intensively vs. extensively managed agroecosystems (McGrath *et al.*, 2020).

- **Developing tools, based on machine-learning approaches, for trait-based insect ecoinformatics research:** Ecoinformatics uses big-data methods to mine large observational databases, such as museum catalogs or citizen-science reports (Rosenheim and Gratton, 2017). Ecoinformatics approaches can address a range of fundamental questions in insect ecology, such as: early detection of the arrival of invasive species, disease vectors or crop pests into new areas; identification of insect migration pathways to allow effective design of ecological corridors; and predicting climate-change effects by monitoring insect densities, activity seasons, body sizes, age distributions and sex ratios along climatic gradients. These potential benefits are still under-exploited, mainly because entomological data acquisition is labor-intensive and requires taxonomical expertise. Consequently, most insect databases are currently too small and sparse for machine-learning applications. To relieve this data acquisition bottleneck, we advocate the combination of “low tech” large-scale capture of insects using sticky traps with “high tech” deep learning. We aim to advance a novel high-throughput and cost-effective approach for monitoring flying insects and their morphological traits, as an enabling step towards “big data” entomology. As part of our project, we will generate a platform for a free internet-based, openly available insect image database, which can be queried, extended and improved in future projects. The database will provide important insights about insect population and community dynamics, distribution ranges, phenology and life-history traits. At the same time, it will generate tools for additional such projects for other organisms, by our team as well as by others.

Detailed description of the proposed research

Working hypotheses: We expect higher herbivore (host) densities in the abandoned vineyards than in the intensively managed plots, which experience regular applications of insecticides and herbicides. Following Segoli & Rosenheim (2013), we thus predict (1) higher fecundity of parasitoids in abandoned plots than in conventional plots, as an adaptation for the increased host abundance. We expect the increased investment in egg production to be traded off with (2) smaller body sizes, (3) smaller eggs and/or (4) shorter adult life spans in parasitoids from unmanaged plots than in those from conventional plots (Segoli & Wajnberg, 2020).

Abandoned plots are also likely to contain more herbaceous annual non-crop vegetation, and hence more nectar sources for parasitoids, than conventional vineyards. The presence of nectar-rich plants can affect parasitoid community composition (Miall *et al.*, 2020). We thus hypothesize (5) a higher dependence of parasitoids from abandoned vineyards on sugar feeding, compared to parasitoids from intensively managed vineyards.

Based on functional trait studies from other insect taxa (Hanson *et al.*, 2016, 2017, Neff *et al.*, 2020, Perović *et al.*, 2018, Rader *et al.*, 2014), we further predict parasitoids in abandoned vineyards to have (6) shorter activity seasons (7) narrower habitat ranges and (8) narrower host ranges than parasitoids from conventional vineyards.

In the periodically unmanaged ‘Sabbatical year’ plots, we predict parasitoids to possess trait values that are intermediate between those recorded in conventional and in abandoned vineyards. We further expect traits associated with intensive vineyard management to become less common in the parasitoid community (both between and within species) during a ‘Sabbatical year’ (in 2022), and increase again in the same plots after intensive agricultural management is resumed.

Research design & methods

General design: We will locate five triplets of wine-producing vineyards in the north of Israel. One vineyard in each triplet will be abandoned, the second will be set-aside during the 2022 ‘Sabbatical year’, and the third will serve as a conventionally managed control. Vineyards within each triplet will be matched for age, cultivar and geographical location. Eliminating differences in landscape context between the paired plots is essential, since landscape-level effects dominate functional community composition even more strongly than in-field management (Gámez-Virúes *et al.*, 2015). All selected vineyards will border with non-crop habitat along at least one of their edges.

We will sample the study plots during the 2022-2024 seasons, namely during the upcoming ‘Sabbatical year’ and the two following seasons. Using this design, we will assess functional traits

of parasitoid communities ([Aim 1](#)) and their pest control effects ([Aim 2](#)) along a gradient of agricultural management intensity: from conventional to transiently unmanaged to permanently unmanaged. These data, combined with comparisons of the transiently unmanaged plots during vs. after the ‘Sabbatical year’, will allow testing for pest control benefits of the ‘Sabbatical year’ tradition ([Aim 4](#)). Much of our sampling will involve large-scale trapping of adult parasitoids and their automated identification and measurement ([Aim 3](#)).

Insect sampling: Ten sticky traps will be placed in each of the vineyards, once a month throughout the three years of fieldwork. Two traps will be placed along the vineyard’s border with the natural habitat, and the remaining ones will be located at regular and increasing distances towards the vineyards’ center. Similarly, we will place ten traps in each natural habitat, at increasing distances from the vineyards’ edge. The traps will be attached to poles at 1.5 m height, removed after one week, photographed, and stored at -20° C for future reference. This sampling design will generate 15 sites × 20 trapping locations × 12 months × 3 years = 10800 traps to be inspected. Using the proposed automated image analysis workflow (see below), we do not anticipate the large number of traps to limit our progress.

Pests and parasitoids in the vineyards are mostly active during the fruit-growth season (April-October). We will introduce 36 young, potted vines into each vineyard at the beginning of each season. These sentinel plants will be exposed to natural infestation by resident herbivores, and to natural enemies attacking those herbivores. We will remove six pots once a month during the 6-month grape-growing period, and will place them individually in emergence cages in the lab for an additional month. Two out of the six cages will be lined with sticky traps to capture as many of the emerging insects as possible. These will be photographed, identified, counted and measured, using the same methods as with the vineyard-placed traps (see below). The remaining four cages will be inspected daily for newly-emerged living parasitoids. These individuals will be used to assess longevity, dependence on sugar feeding, egg loads and egg sizes, as detailed below.

Identifying, counting and measuring parasitoids: Our previous work shows that a small number of species dominate the parasitoid communities in the vineyards of northern Israel (Möller *et al.*, submitted, and preliminary results Table 1). We will focus on these species, because we expect them to be sufficiently common for studying intra-specific trait variation. Other common species, if encountered, will be added along the study.

We will use a custom-ordered pipeline (such as the systems produced by Cognex for quality tests of industrial products) to automatically photograph the field-collected sticky traps at high resolution. We will then manually annotate ~500 individuals of each of the dominant species in the images. Based on these annotations, we will train our deep-learning software to discriminate

the dominant species from one another and from other objects in the images (such as other arthropods, leaves and dust). The existing deep-learning model is already capable of performing such discrimination tasks with high accuracy (for a proof of concept from a different study system, see preliminary results Fig. 4, Keasar *et al.*, submitted). We will develop the software further to conduct measurements of head width (as a proxy of body size) on all individuals of the dominant species. This part of the work will be done in collaboration with Prof. Chen Keasar of the Department of Computer Science, Ben Gurion University (see attached letter of cooperation). Thus, we will gain information on the abundances, composition and body sizes (**hypothesis 2**) of dominant parasitoids on each sticky trap.

We will associate the species abundance data with the traps' metadata (date, site, habitat, with/without 'Sabbatical year' management) to learn about the following life-history traits:

Phenology (hypothesis 6): Each species' activity season will be estimated based on its capture dates.

Habitat breadth (hypothesis 7): We will calculate each species' proportion of captures in vineyard vs. natural habitat as a rough measure of their habitat preferences. In finer-grained analyses, we will relate species abundances to the traps' distances from the vineyards' center.

Longevity and sugar-dependence assays: A subset of the newly-emerged adults from the emergence cages will be kept unfed in individual vials, under standard insectary conditions (25°C, 70% humidity, 12:12 L: D cycle). We will record the parasitoids' survival once a day (**hypothesis 4**). Sample sizes will be at least 10 male and 10 female individuals from each species, originating from each of the following habitat types: conventional vineyards, 'Sabbatical year' vineyards, abandoned vineyards and natural habitat. Other groups of parasitoids (with the same sample sizes) will be provided with honey as a sugar source, and monitored for survival using an identical protocol. We will analyze the data for the effect of source habitat on longevity (between and within species). We will use the difference in longevity between honey-fed and unfed individuals of the same species to estimate their dependence on sugar feeding (**hypothesis 5**).

Egg production and egg volumes: A second subset of newly-emerged females will be dissected and the number of mature eggs in their ovaries determined (using Keinan *et al.*'s 2017 protocol, **hypothesis 1**). We will measure the length and width of the three largest eggs in each female's ovaries, and will estimate egg volume (as in Segoli & Rosenheim, 2013, **hypothesis 3**). This will be done for 10 females from each species-habitat combination.

Host ranges: We will consult with expert taxonomists to determine the dominant parasitoids to species. We will estimate their host ranges (**hypothesis 8**) using published databases and keys.

Pest control estimates: The ratios of parasitoids to herbivores from the emergence traps will provide a rough estimate of community-level pest suppression in the vineyards. To estimate per-capita pest suppression success, we will correct for parasitoid densities as assessed from the sticky trap data.

Environmental variables: We will collect information from the growers on the type and dates of agrochemical (herbicide, pesticide and fertilizer) applications to the vineyards, as indicators of disturbance. To estimate habitat complexity, we will record the richness of non-crop plant species in and near the vineyards. To estimate the availability of sugar for adult feeding, we will sample the density of flowers that are potential nectar sources for parasitoids (nectar-producing species with shallow-flowered complex inflorescences, Zhu *et al.*, 2020). We will also sample the density of aphids on the non-crop vegetation, as a measure of honeydew availability.

Statistical analyses: We will combine the RLQ and Fourth-Corner methods to analyze the links between parasitoid traits (averaged per species or per population) and the environmental conditions in the natural habitat, abandoned, ‘Sabbatical year’, and conventional plots. Both methods require construction of three data tables: table R provides data of environmental variables by sample sites, table Q contains traits by species information, and table L report the abundances of species in each of the sampling sites. These data form the input for the construction of a fourth table, which describes the intensity of the links between the species traits and the environmental variables. In RLQ, the fourth table is used to summarize the main structures in the data along orthogonal axes and provides a global measure of the association between environmental variables and traits (Dray *et al.*, 2014). It allows to identify trait syndromes of species sharing similar traits and reacting similarly to different environments, as demonstrated for arthropod communities in grasslands (Gómez-Virués *et al.*, 2015, Neff *et al.*, 2020). In the Fourth-Corner analysis, the table is used to evaluate the multiple bivariate correlations between traits and environmental variables, accounting for biases generated by highly correlated traits. This method was successfully applied to life-history traits of butterflies along a gradient of land use intensity (Börschig *et al.*, 2013). By combining the two methods, one can test the global significance of the trait–environment relationships using multivariate statistics, and also explore how individual functional traits change with environmental gradients (Méndez-Toribio *et al.*, 2020).

To explore the effects of environmental variables (field management, year, climate, and habitat) on the abundance of individual species, we will use general linear mixed models. We will use the plots’ location as a random factor in the models, to account for the paired sampling design.

Preliminary results

Fig. 1: Species richness and abundance of parasitoids of three guilds (attacking leafhopper, whiteflies and leafminers) in Israeli pomegranate agroecosystems. The Venn diagrams indicate the number of species sampled on the pomegranate trees, in the weeds below the trees, in natural habitat beside the orchards, or in more than one habitat. Several species were restricted to the natural habitat, illustrating the filtering of some species by conditions in the orchard.

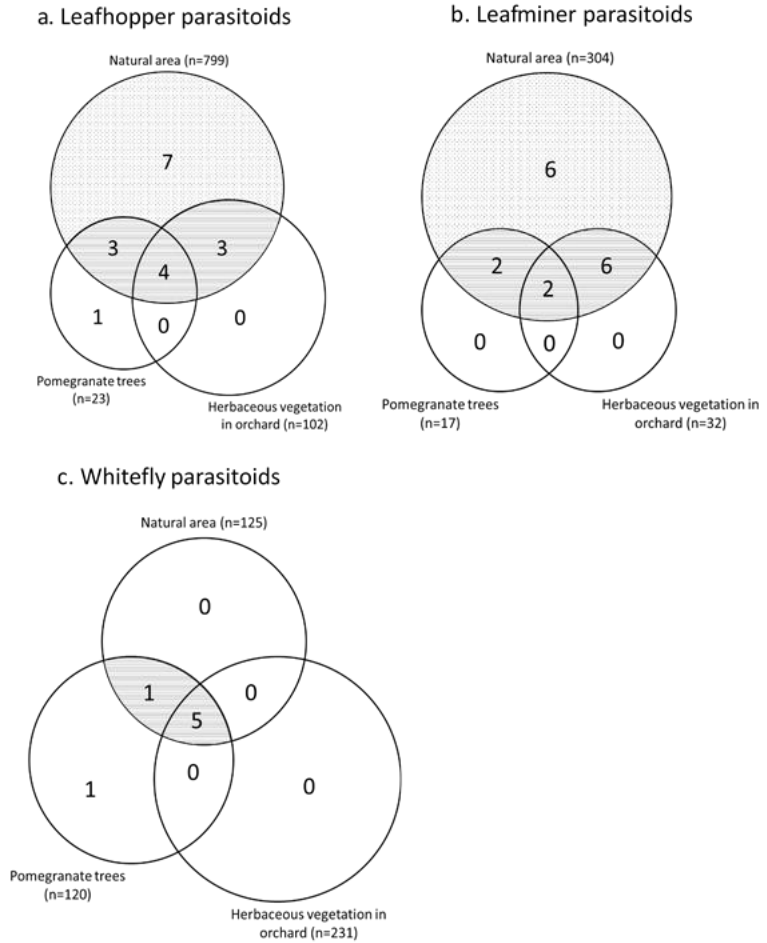
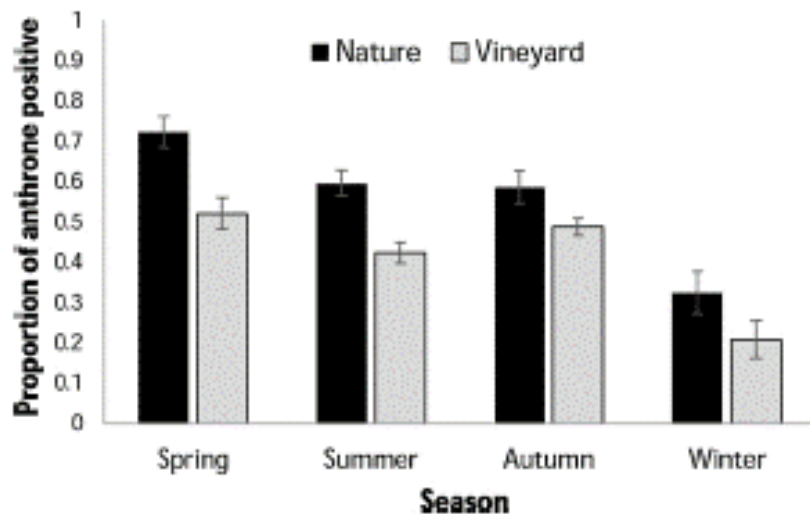


Fig. 2: Community-wide frequencies of sugar-feeding in parasitoids from Israeli vineyards and neighboring natural habitat along the different seasons. Sugar-feeding frequencies were estimated using qualitative cold anthrone tests. The frequency of sugar-fed parasitoids in the vineyards was significantly lower than in the natural areas, and was lower than 0.5 in all seasons, suggesting that sugar is a limited resource for adult parasitoids in intensively managed vineyards. For further details, see Kishinevsky & Keasar (2021).



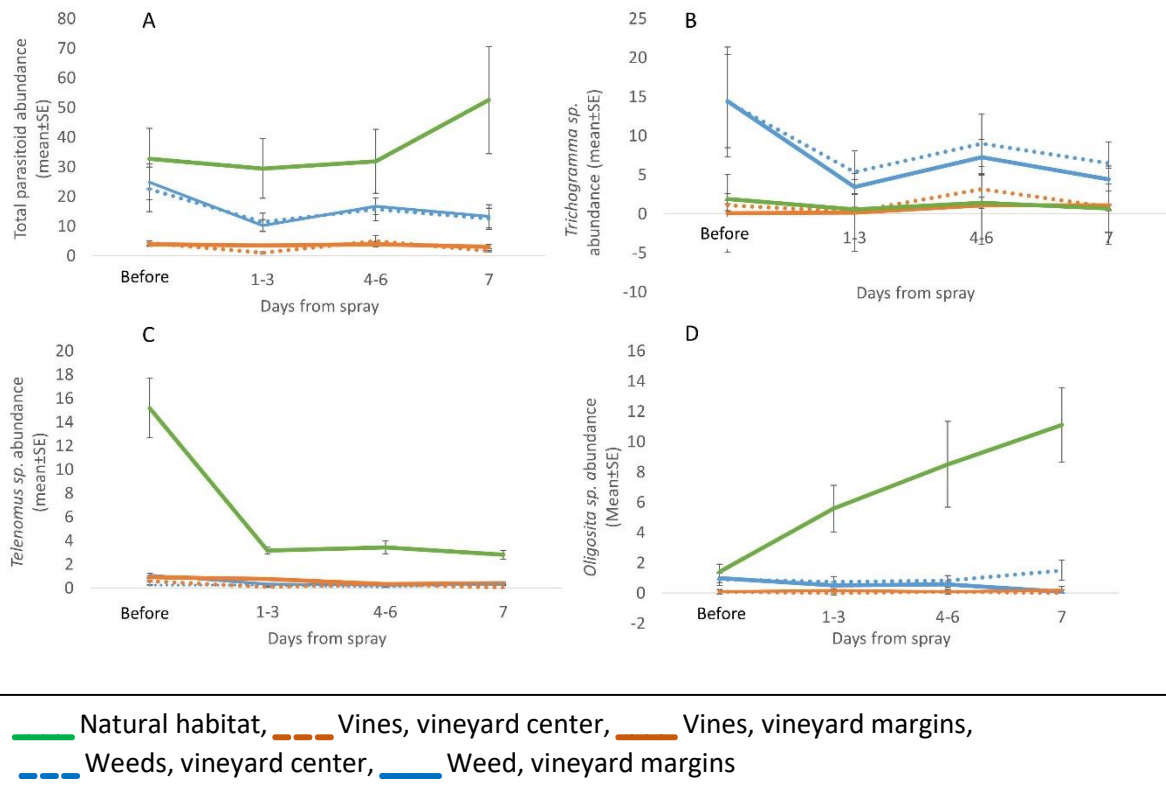


Fig. 3: A - Total parasitoid abundance in vineyards before (Day 0) and after (Days 1-7) spray applications of Indoxacarb, a ‘soft’ insecticide aimed to control lepidopteran larvae. B-D – illustrations of the effects of the insecticide on the abundances of three common egg parasitoids: *Trichogramma sp.* (B), *Telenomus sp.* (C), and *Oligosita sp.* (D). The data are based on six vineyards sampled in 2019. Note the differences among species in habitat use, and their differential non-target response to the insecticide (Schindler *et al.*, unpublished data).

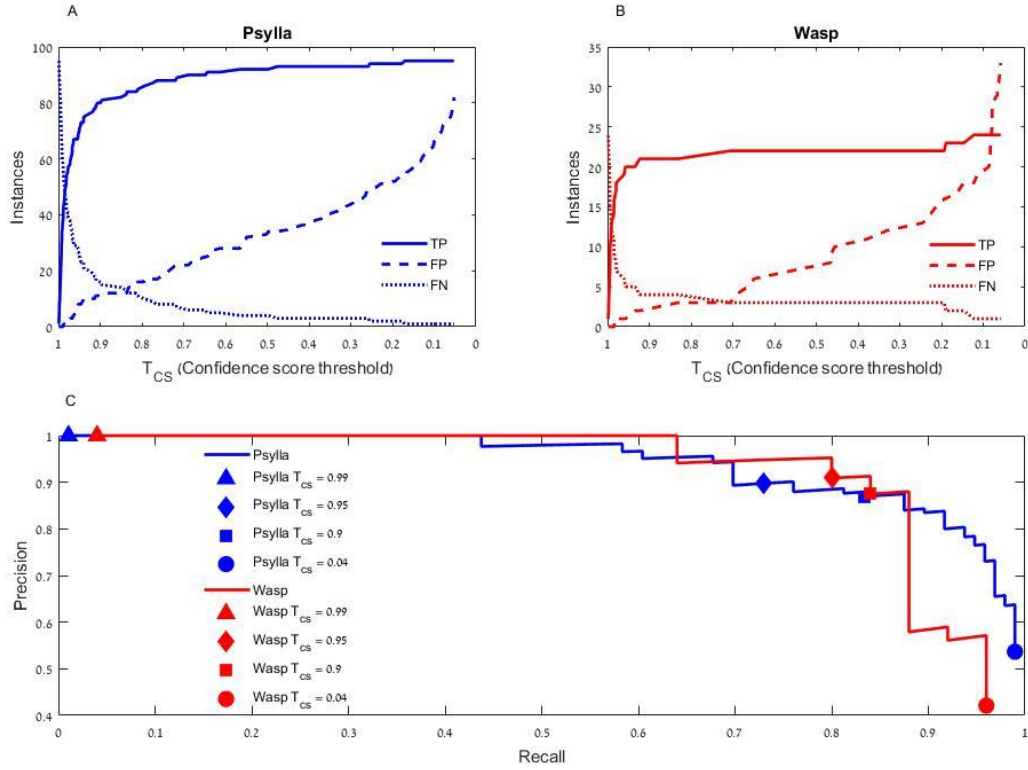


Fig. 4: Illustration of the performance of a deep learning model, trained to identify a hemipteran forest pest (‘Psylla’) and its parasitoid natural enemy (‘Wasp’) in images of sticky traps. The top panels depict the model’s performance as a function of its stringency (the confidence score threshold, plotted on the x-axes). The difference performance measures are plotted separately for the two identification tasks, namely identifying “Psylla” vs. non-“Psylla” (top left), and “Wasp” vs. non-“Wasp” (top right). For both tasks, as the model becomes more permissive, it makes more true-positive (TP) and fewer false-negative (FN) identifications. On the other hand, the number of false-positive (FP) identifications increases as well. This tradeoff is formulated in the concepts of recall (% of ‘Psyllas’ or ‘Wasps’ in the images identified by the model) and precision (% of ‘Psylla’ or ‘Wasp’ predictions that are correct), and is visualized by a Precision-Recall plot (bottom). Each data point on this plot depicts the recall (x-coordinate) and precision (y-coordinate) associated with a particular stringency level (T_{CS}). Model stringency decreases along the X-axis. Thus, the leftmost data points denote the proportion of insects detected (recall), and the fraction of predictions that are correct (precision), when the model requires the highest confidence score to predict the type of insect in the image. The rightmost data points describe the performance attained by a model that accepts all identifications, as its T_{CS} is minimal (Keasar *et al.*, submitted).

Fig. 5: An illustrative sticky traps, hung in a conventional vineyard in June 2019, and retrieved a week later. Trapped parasitoids are marked with circles. The checkerboard target is a 2×2 cm scale bar.

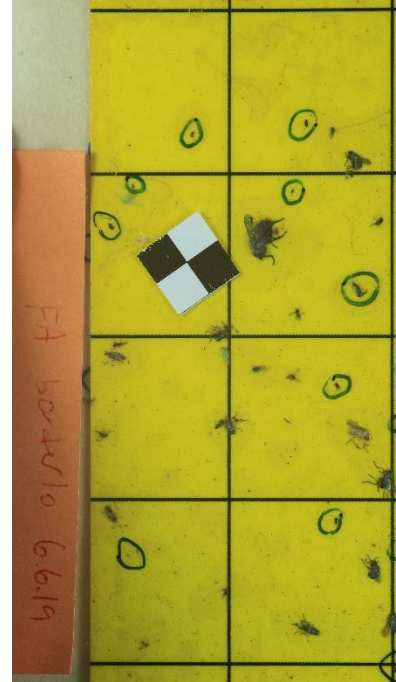


Table 1: Common parasitoids species/morphospecies in our previous studies of vineyards in northern Israel. Species are listed in alphabetical order. The list is compiled from Shapira *et al.* (2018), Möller *et al.* (submitted), and unpublished data by Schindler *et al.*

Species/morphospecies	Family	Main habitat	Geographical area
<i>Anagrus</i> sp.	Mymaridae	Natural, Vineyard	Carmel, Galilee
<i>Anagyrus</i> sp. nr. <i>pseudococci</i>	Encyrtidae	Natural, Vineyard	Galilee
<i>Ceranisia</i> sp.	Eulophidae	Vineyard	Galilee
<i>Cirrospilus</i> sp.	Eulophidae	Natural	Galilee
<i>Encarsia lutea</i>	Aphelinidae	Vineyard	Galilee
<i>Eretmocerus</i> sp.	Aphelinidae	Vineyard	Galilee
<i>Lymaenon litoralis</i>	Mymaridae	Natural, Vineyard	Carmel, Galilee
<i>Neochrysocharis formosus</i>	Eulophidae	Natural	Galilee
<i>Oligosita</i> sp.	Trichogrammatidae	Natural, Vineyard	Carmel
<i>Telenomus</i> sp. 1	Platygastridae	Natural, Vineyard	Carmel, Galilee
<i>Telenomus</i> sp. 2	Platygastridae	Natural, Vineyard	Galilee
<i>Trichogramma</i> sp.	Trichogrammatidae	Vineyard	Carmel

Available resources and infrastructure

Our lab is equipped with freezers, incubators, light microscopes, dissection microscopes, insect cages and other standard entomological equipment. A departmental vehicle is available for fieldwork. A greenhouse is available at the Oranim botanical garden for growing the sentinel plants. We set up a temporary website, which allows storing sticky trap images in a database, and running the deep-learning software to identify selected insects of the images.

Possible pitfalls and solutions

(1) The sentinel plants might not attract herbivores and parasitoids in sufficient numbers. *Solution:* if needed, we will complement the sentinel plants with collections of infested leaves and fruit from the vineyards. We will use adult herbivores and parasitoids that emerge from the leaves and grapes for the lab work, using similar procedures as for the sentinel plants.

(2) A single ‘Sabbatical year’ may not suffice to affect the species and trait distributions in parasitoid communities. *Solution:* If we find no difference between ‘Sabbatical year’ and conventional vineyards in 2022, we will focus on comparing conventional and abandoned vineyards during this year. We will add organic vineyards to our sampling plan in 2023-2024, to represent plots with intermediate management intensity levels.

(3) The deep-learning software might fail to distinguish between similar-looking, related parasitoids (such as the two *Telenomus* species listed in Table 1). *Solution:* Such complex discrimination tasks may require complex network architectures and feature engineering (informing the model which morphological traits are important for specific classification tasks). As part of our collaboration with a machine-learning expert (see letter of cooperation), we will improve and update the computational network as needed.

Bibliography

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