DROP: Molecular voucher database for identification of *Drosophila* parasitoids

Resource article

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Abstract

Molecular identification is increasingly used to speed up biodiversity surveys and laboratory experiments. However, many groups of organisms cannot be reliably identified using standard databases such as GenBank or BOLD due to lack of sequenced voucher specimens identified by experts. Sometimes a large number of sequences are available, but with too many errors to allow identification. Here we address this problem for parasitoids of *Drosophila* by introducing a curated open-access molecular reference database, DROP (*Dro*sophila parasitoids). Identifying *Drosophila* parasitoids is challenging and poses a major impediment to realize the full potential of this model system in studies ranging from molecular mechanisms to food webs, and in biological control of *Drosophila suzukii*. In DROP (http://doi.org/10.5281/zenodo.4519656), genetic data are linked to voucher specimens and, where possible, the voucher

specimens are identified by taxonomists and vetted through direct comparison with primary type material. To initiate DROP, we curated 154 laboratory strains, 856 vouchers, 554 DNA sequences, 16 genomes, 14 transcriptomes, and 6 proteomes drawn from a total of 183 operational taxonomic units (OTUs): 114 described *Drosophila* parasitoid species and 69 provisional species. We found species richness of *Drosophila* parasitoids to be heavily underestimated and provide an updated taxonomic catalogue for the community. DROP offers accurate molecular identification and improves cross-referencing between individual studies that we hope will catalyze research on this diverse and fascinating model system. Our effort should also serve as an example for researchers facing similar molecular identification problems in other groups of organisms.

Key Words

Biodiversity, DNA sequences, Genomes, Integrative taxonomy, Molecular diagnostics, Biological control

Introduction

Building a knowledge base that encompasses ecology, evolution, genetics, and biological control is contingent on reliable taxonomic identifications. Molecular identification is commonly used in groups of organisms with cryptic species that are difficult to identify morphologically (Fagan-Jeffries et al., 2018; Miller et al., 2016; Novotny & Miller, 2014), for the molecular detection of species interactions (Baker et al., 2016; Condon et al., 2014; Gariepy et al., 2019; Hrček & Godfray, 2015; Hrcek et al., 2011), and for identification of species from environmental DNA samples (Shokralla et al., 2012). The accuracy of molecular identification, however, depends on the accuracy of identifications associated with sequences databased in existing online depositories (Fontes et al., 2021). The foundations of that accuracy are the voucher specimens which were sequenced and the collaboration of a taxonomic authority in the deposition of the sequence data.

GenBank serves as the most widely used sequence depository; however, deposition of sequences in GenBank, which is required by most peer-reviewed journals, does not require deposition of associated vouchers. The Barcode of Life Data System database (BOLD) (Ratnasingham & Hebert, 2007) explicitly aims to provide a framework for identifying specimens using single-locus DNA sequences (Hebert et al., 2003; Smith et al., 2005), and while these are associated with vouchers and metadata, the curation of these data is not consistently maintained by those submitting material. A recent study by Pentinsaari et al. (2020) showed misidentification in both databases caused by missteps in the protocols from query sequences to final determination.

Although the BOLD database function "BOLD-IDS" allows considerable database curation (e.g. flagging of misidentified/contaminated records), it also automatically includes sequences from GenBank, and may perpetuate the shortcomings previously mentioned since these cannot be curated from within BOLD. As such, the quality of sequences and the reliability of identifications obtained from BOLD-IDS can vary, and depends on the curation by taxonomists focusing on individual taxa (Meiklejohn et al., 2019). BOLD-IDS works well for taxa where qualified taxonomists have been involved with assuring data quality; some insect examples include beetles (Hendrich et al., 2015), butterflies (Escalante et al., 2010), geometrid moths (Hausmann et al., 2011, 2016; Miller et al., 2016), true bugs (Raupach et al., 2014), and microgastrine wasps (Smith et al., 2013).

Unfortunately, this is not the case of parasitoids (Insecta: Hymenoptera) of *Drosophila* flies (Insecta: Drosophilidae). There are vast numbers of *Drosophila* parasitoid sequences readily available in GenBank and BOLD, as these parasitoids and their hosts are important model organisms in biology. As of this writing, there are 88,666 nucleotide sequences deposited in GenBank for *Leptopilina heterotoma* (Thomson) and *L. boulardi* (Barbotin, Carton & Kelner-Pillault) (Hymenoptera: Figitidae) alone. However, less than 1 % of the identifications associated with these sequences have been confirmed by taxonomists or are associated with voucher specimens deposited in museum collections. With sequencing shifting from individual genes to genomes we risk that the identification problems will soon apply to whole genomes.

Drosophila and their parasitoids

The phylogenetic and subgeneric structure within *Drosophila* and related genera is not yet fully resolved (O'Grady & DeSalle, 2018). Various subgenera, including *Scaptomyza*, *Zaprionus*, *Lordiphosa* and *Samoaia*, have been treated as both genera and subgenera, and researchers have yet to achieve consensus on these various hypotheses (O'Grady & DeSalle, 2018; Remsen & O'Grady, 2002; Yassin, 2013; Yassin & David, 2010). Species in *Drosophila* subgenera and genera closely related to *Drosophila* commonly share niche space and natural histories and, as a result, are often attacked by overlapping or identical groups of parasitoids. For instance, the invasive African fig fly, *Zaprionus indianus* Gupta is attacked by *Pachycrepoideus vindemiae* (Rondani, 1875) and *Leptopilina boulardi* (Pfeiffer et al., 2019; Santos et al., 2016), all of which have been recorded from *Drosophila*. Therefore, we also include these groups within the contents of DROP.

Parasitoids of *Drosophila* belong to four superfamilies of Hymenoptera (Chalcidoidea, Cynipoidea, Ichneumonoidea, Diaprioidea) which evolved parasitism of *Drosophila* flies independently. All the parasitoids known to attack *Drosophila* are solitary and attack either the larval or pupal stage; in both cases, they emerge from the fly's puparium (Carton et al., 1986; Prévost, 2009). The known *Drosophila* larval parasitoids belong to two families (Table 1), Braconidae (including the genera *Asobara, Aphaereta, Phaenocarpa, Tanycarpa, Aspilota, Opius*) and Figitidae (*Leptopilina, Ganaspis, Leptolamina, Kleidotoma*); all are koinobionts that allow the host to continue development while the parasitoid grows within it. The known *Drosophila* pupal parasitoids belong to three other families (Table 1), Diapriidae (*Trichopria, Spilomicrus*),

198 Pteromalidae (*Pachycrepoideus, Spalangia, Trichomalopsis, Toxomorpha*) and Encytidae
199 (*Tachinaephagus*); they are all idiobionts that terminate host development immediately.
200 Host-specificity across the *Drosophila* parasitoids is poorly characterized—while some
201 can parasitize other families of Diptera (e.g., *Aphaereta aotea*) (Hughes & Woolcock,
202 1976), most are thought to be limited to *Drosophila* hosts.

203 There are around 4000 described species of Drosophilidae, and *Drosophila* contains
204 more than a third of the family's described species (O'Grady & DeSalle, 2018). By
205 contrast, although parasitic wasps are generally a species-rich group (Dolphin & Quicke,
206 2001; Quicke, 2015), the most recent catalogue of parasitoid species that attack
207 *Drosophila* lists only 50 described species (Carton et al., 1986). This disparity suggests
208 that the diversity of parasitic wasps attacking *Drosophila* is severely underestimated, an
209 assertion supported by the results presented here. This is largely a consequence of the
210 challenging nature of parasitoid taxonomy, in which morphological identification is
211 intractable for many species, and the fact that taxonomic specialists are greatly
212 outnumbered by the species they study.

213 Currently, only a few biological study systems have been characterized in
214 sufficient breadth and depth to allow researchers to connect various levels of biological
215 organization, from molecular mechanisms to food webs of interacting species.
216 Parasitoids of *Drosophila* represent one such system (Prévost, 2009). Moreover, the
217 practical feasibility of rearing parasitoids of *Drosophila* under laboratory conditions has
218 led to a number of fundamental discoveries in ecology (Carton et al., 1991; Terry et al.,
219 2021), evolution (Kraaijeveld & Godfray, 1997), immunology (Kim-Jo et al., 2019; Nappi

& Carton, 2001; Schlenke et al., 2007), physiology (Melk & Govind, 1999), symbiosis (Xie et al., 2011, 2015), behavioral science (Lefèvre et al., 2012) and other fields. In contrast to this large body of laboratory studies, basic natural history of *Drosophila* parasitoids, especially their species richness is little known (Kimura & Mitsui, 2020; Lue et al., 2018). Addressing this knowledge gap is especially pressing given current efforts to use parasitoids in biological control efforts, such as those of the invasive pest spotted wing *Drosophila*, *Drosophila suzukii* (Abram et al., 2020; Daane et al., 2016; Giorgini et al., 2019; Wang et al., 2020 a&b).

Properly executed molecular identification has the potential to be much more efficient for the majority of researchers, and many laboratory strains are commonly identified using DNA sequences alone. While it is practical for researchers to assign species names based on a match to sequence records in genetic databases, this practice often causes a cascade of inaccuracies. To illustrate the extent of the problem, we present the example of *Ganaspis,* a genus of parasitoids commonly used in laboratories that includes both superficially indistinguishable species with highly divergent sequences that are often treated as conspecific, as well as specimens with identical sequences identified under different names (Figure 1).

Aims

To address these issues, we introduce a newly curated molecular reference database for *Drosophila* parasitoids —DROP— in which sequences are either linked to voucher specimens identified by taxonomists or have a traceable provenance (Figure 2). The first aim of DROP is to provide a reliable DNA sequence library for molecular identification of

242 *Drosophila* parasitoids that enables cross-referencing of original taxonomic concepts
243 with those of subsequent studies. We pay special attention to live parasitoid strains
244 which are available for future experiments. The second aim is to standardize and
245 expedite the linkage between specimens and available sequence data; we place a
246 premium on museum vouchers as they allow for repeatable scientific research. In DROP,
247 this goal is facilitated through a consolidated digital infrastructure of data associated
248 with laboratory strains, offering the opportunity for researchers to re-examine past
249 experimental results in a permanent context. The third aim is to provide an up-to-date
250 catalogue of the diversity of *Drosophila* parasitoids as a foundation for advancing the
251 understanding of their taxonomy. Finally, the fourth aim of DROP is for our collaborative
252 effort to serve as an inspiration to communities of researchers studying other groups of
253 organisms who are experiencing difficulties with the reliability of molecular reference
254 databases.
255
256 **Materials and Methods**
257 ***Data sources***
258 To assemble the DROP database, we targeted 20 wasp genera that potentially
259 parasitize frugivorous *Drosophila* species. We compiled DNA sequence and voucher data
260 from four sources: 1) museum collections, 2) publications, for which we selected the
261 reference with taxonomist or parasitoid biologists as coauthors to ensure reliable
262 species identity, 3) molecular biodiversity inventories publicly available in BOLD and

GenBank, for which we managed to secure inspection of the vouchers by taxonomists, and 4) a sequencing and taxonomic inventory of laboratory strains we conducted.

We first gathered species information into a catalogue of *Drosophila* parasitoid species (Table 1) from 216 references (see DROP database reference table) and 36 institutes (Table S2). To ensure reliable names for nominal species (sequences identified by a species name) in our database, we confirmed their taxonomic validity using the Ichneumonoidea 2015 digital catalogue (Yu et al., 2016) and Hymenoptera Online (HOL; http://hol.osu.edu/), both of which are curated by taxonomic experts. To obtain reliable molecular identification data, we harvested 8,298 DNA sequences from GenBank and BOLD (all compiled in BOLD as DS-DROPAR dataset dx.doi.org/10.5883/DS-DROPAR). As of writing, these sequences represented 445 Barcode Index Numbers (BINs – a form of dynamic provisionary taxa in BOLD, more detail in Ratnasingham & Hebert 2013), and 211 named taxa.

The majority of the harvested sequences were Braconidae (6690), Diapriidae (967), Figitidae (622), and Pteromalidae (19). Because of the concerns with generic databases (noted above and in Figure 1 and Table S1), we assembled a list of sequences with valid species names that could either be traced back to vouchers examined by taxonomists or were referred to directly in publications authored by a recognized expert in the relevant taxon group. We then cross-checked species names with their corresponding BINs in BOLD and flagged potential conflicts between species names and BINs (Table S1).

A core goal of DROP besides that of a tool for biodiversity research is to function as a platform that accommodates *Drosophila* parasitoids kept in laboratory strains (for experimental work) or cultures in quarantine facilities (for biological control applications). So far, there has been a lack of a coherent and reliable means of verifying identification of species kept in laboratory settings, which can be a serious problem. Since lab cultures are routinely contaminated by neighboring cultures (e.g., through escapees), one species may be displaced by another even under a vigilant eye.

For lab and quarantine lines in DROP, we deposited DNA extractions and vouchers in the National Insect Collection, National Museum of Natural History, Smithsonian Institution (USNM; Washington, DC, USA). During their initial assembly of DROP, laboratory OTUs (operational taxonomic unit) were designated by their strain name; most laboratory strains can be associated with provisional species, but some cannot yet be assigned. Three females and three males of each strain were dry-mounted and individually assigned a USNMENT 'QR code' specimen label as representative vouchers. For each molecular voucher, three legs from a female wasp were removed for DNA extraction and sequencing (Supplementary Methods for details), and the rest of the body was assigned a USNMENT specimen label and preserved for morphological identification. Both DNA extraction and vouchers were entered into the database and uploaded to BOLD (DROP project: DS-LABS dx.doi.org/10.5883/DS-LABS) with an associated GenBank ID.

Where possible, we identified OTU strains using a combination of morphological and sequence data, and characterized provisional species or species clusters using neighbor-

joining trees (Figure S1) based on the COI gene sequences (Supplemental material). For establishing BIN limits in the context of DROP, we have adopted an initial percent cutoff at 2%. We acknowledge that 2% genetic diverge cutoffs (or BINs) are unlikely to work well across range of widely distributed species (Lin et al., 2015). But as Ratnasingham & Hebert (2013) pointed out, 2% is a good starting point for many taxa, also it may need to be adjusted as more samples are acquired and compared. Note that we use the term "OTU" as a general and neutral designation encompassing described species, provisional species, undescribed species, and cryptic species.

Drosophila parasitoid database—DROP

To compile the above information, we built a simple Structured Query Language (SQL) database in sqlite3 format using SQLiteStudio (step by step user instruction in supplemental material). Sqlite3 is a cross-platform format which can be also be opened using a number of other programs. There are eight linked tables in the database — species, strain, voucher, sequence, genome, transcriptome, proteome and reference — along with additional tables for linking these to reference table (Figure S2). The database incorporates all sample fields used by BOLD for compatibility and includes a number of new fields to accommodate a catalogue of *Drosophila* parasitoid species, laboratory strain information, and links from the DROP database to BOLD and GenBank records.

DROP is available on Zenodo (http://doi.org/10.5281/zenodo.4519656) for permanent deposition and version control. In addition to the main database, the

Zenodo repository includes additional files to facilitate easy use of the database. These files include: 1) the reference database in comma-separated text (.csv) and FASTA format ready to be used for molecular identification; 2) a species catalogue with taxonomic information; and 3) a list of laboratory strains with confirmed molecular vouchers. DROP will be continued to be curated and maintained by C-HL at the Zenodo repository and sequences generated in the future will also be deposited in BOLD (DROP project). If the curator changes, this will be announced in the README.md file in Zenodo repository. As the database relies on vouchers, we will aim for it to be continued to be maintained by taxonomists with direct access to museums.

Species, provisional species, and OTU designations

In addition to the inherent value of a formal taxonomic name, a reliable provisional taxon label can also be used for exchanging scientific information and conveying experimental results among researchers (Schindel & Miller, 2010). Based on the amount of sequence divergence between described species, we observed what appears to be a significant number of provisional OTUs in the initial dataset we compiled. Furthermore, among the data linked to a valid species name, some of these provisional OTUs are actively being used in research and have sequences available to the public. We therefore provide a list of provisional species (potential new species) with their molecular vouchers.

We use the following designation format for OTUs that refer to a provisional species: “Drop_strainX_sp.1” or, when no other information is known, “DROP_sp.1”. Where

possible, these OTUs are linked to a voucher USNM specimen label number. If the genus of the OTU is known, the "Drop_Leptopilina_sp.1" format is followed. These designations can facilitate species identification as well as discovery and description of new species without compromising the existing taxonomy of the described OTUs in question. As more complete species descriptions become available, this provisional species framework can be updated while keeping the link to previous provisional species name through deposited vouchers.

Results

Overview of DROP

We catalogued 183 OTUs in the DROP database with 114 described species of *Drosophila* parasitoids and 69 provisional species (Table 1). In total, we documented 154 laboratory strains (Table S3), and 853 vouchers from 36 institutions (Table S2). Among the described species, 98 have voucher information, of which 61 are traceable to type specimens, including 45 to holotypes (i.e., specimen used to root a name to the taxonomic author's concept of the species). *Leptopilina* is represented by the highest number of species with 45 OTUs, followed by *Asobara* with 26 OTUs. Within the 154 catalogued lab strains, 86 were actively being used in ongoing research (i.e., a live strain being cultivated). These strains represent 39 OTUs: 11 described species and 28 provisional species (Table S3, Figure S1).

Molecular Vouchers

So far, DROP includes 545 DNA sequences and links to 16 genomes (Table S4), 14 transcriptomes (Table S5), and 6 proteomes (Table S6). From the total of 8298 DNA sequences (BOLD dataset: DS-DROPAR) collected from public databases, only 322 sequences (less than 4% of available sequences) satisfied the reliability criteria we imposed for molecular vouchers to be included in DROP (see Materials and Methods). The DS-DROPAR dataset dx.doi.org/10.5883/DS-DROPAR initially referred to 211 taxon names, but only 52 names were valid, linked to vouchers, or linked to a publication with evidence that the specimens had been identified by taxonomists. The remaining 223 of 545 DROP DNA sequences were generated by DROP project (datasets: DS-LABS dx.doi.org/10.5883/DS-LABS and DS-AUSPTOID dx.doi.org/10.5883/DS-AUSPTOID) and came from 121 OTUs (101 lab strains and 12 provisional species).

The DROP database is largely made up of standard barcode COI sequences (349 sequences), which includes 77 OTUs: 43 described species and 33 provisional species. We aimed to supplement COI with secondary markers (28SD2, 18S, ITS2) when possible, resulting in an additional 120 sequences from 26 OTUs: 15 described species and 11 provisional species. There are currently 19 OTUs that have sequences from more than one genetic marker.

Species Delimitation in Laboratory Strains

We used 298 COI sequences to resolve the identification of each laboratory strain, and where possible, indicated potential species clusters (Fig. S1 and Table S3). Using a fixed 2% divergence cutoff, a total of 31 lab strain OTUs were assignable to a

394 valid species name, and the remaining 70 strain OTUs were assigned to a provisional
395 species. The taxonomic status of several of these provisional species is also being
396 investigated using an integrative taxonomic approach involving morphological
397 identification, genomic data, or other genetic data.

398

399 **Discussion**

400 In this paper, we introduce and describe a free and open-access database for the
401 reliable molecular identification of *Drosophila* parasitoids. The guiding principle of DROP
402 is data credibility, based on the prerequisite that genetic data are explicitly associated
403 with voucher specimens and taxonomic concepts of the original authors (Troudet et al.,
404 2018). When incorporating information from public genetic databases, we included only
405 sequences that have passed our filtering protocol. This protocol ensures each entry is
406 associated with a valid scientific name, provisional name, or consistently applied OTU
407 designation that can be used to integrate genetic and organismal data from
408 independent studies.

409 The following discussion expands on the utility of DROP and how we hope it will
410 benefit molecular species identification, connect research from various disciplines,
411 support biological control applications, and serve as a long-term molecular voucher
412 repository and clearinghouse for vetted data. We also provide specific guidance for
413 users how best to refer to DROP in their publications to allow cross-linking between
414 studies.

415

416 ***Molecular (mis-)identification***

417 We observe that 17% of the described *Drosophila* parasitoid OTUs in BOLD and
418 GenBank (dataset: DS-DROPAR) are associated with more than one BIN; these are
419 examples of BIN-ID conflict. Roughly half of these OTUs are used as lab strains. This
420 latter observation is disturbing, because it demonstrates that the criteria used to
421 differentiate and reference species in active research programs are clouded. For
422 example, BIN-ID conflicts were observed in the *Drosophila* parasitoids *Ganaspis*
423 *brasiliensis* (Ihering) and *Asobara japonica* Belokobylskij (Table S1), both of which are in
424 active use in numerous research programs (e.g. Moreau et al., 2009; Nomano et al.,
425 2017; Reumer et al., 2012; Wang et al., 2020a & 2021) as well as in biological control
426 efforts against the invasive *D. suzukii* (e.g. Abram et al., 2020; Daane et al., 2016;
427 Giorgini et al., 2019). All the BINs from *G. brasiliensis* carry the name *G. xanthopoda*
428 (Figure 1). In such instances, assigning an identification by matching specimens to
429 barcode records in the genetic database is problematic, as two names are applied to the
430 same BIN. If sequences comprising the BIN are not linked to a voucher that can be
431 examined, teasing apart the two names and how they are applied is impossible.
432 Applying explicit, consistent criteria for species determination ensures that
433 experimental results can be reliably repeated, and that any potentially novel
434 observations will not be explained away as artifacts of identification. DROP addresses
435 these concerns by linking reliable reference sequences and vouchers for *G. brasiliensis*
436 (Figure 1) between different studies: one with reference to the morphological

437 description (Buffington & Forshage, 2016) and the other with reference to the genome
438 (using voucher specimens from the morphological study; Blaimer et al., 2020).
439 We were not able to resolve all conflicts between BIN and species identity, for one
440 or more of the following three reasons: First, many records lack reliably identified
441 vouchers and have often been themselves used for molecular identification,
442 proliferating errors. Second, in some cases, it is not possible to verify whether the
443 genetic differences among BINs represent different species or simply intraspecific
444 genetic variation (Bergsten et al., 2012), because BINs themselves are not a species
445 concept. The only solution to this problem is to derive original sequence data from type
446 specimens (which is often either impractical or impossible for a number of technical
447 reasons), or from specimens whose conspecificity with the types has been corroborated.
448 Since species boundaries are always subject to testing, additional specimens from
449 multiple collecting events (ideally representing different seasons and geographic
450 regions) may help provide the additional data to circumscribe a given species' limits. The
451 third difficulty in resolving BIN-ID conflict derives from the data themselves: Although
452 the mitochondrial COI gene is the locus most frequently chosen for identification of
453 insects and other animals, its effectiveness varies among insect groups (Brower &
454 DeSalle, 2002; Gompert et al., 2008; Lin & Danforth, 2004). In part, this derives from
455 gene-tree/species-tree conflict as a function of mitochondrial DNA introgression
456 (Gompert et al., 2008; Klopfstein et al., 2016), parthenogenesis (Reumer et al., 2012),
457 and/or *Wolbachia* infection (Ferrer-Suay et al., 2018; Wachi et al., 2015; Xiao et al.,
458 2012), any of which may lead to complications in species delimitation using

mitochondrial loci. Ideally, studies should apply multiple loci, genomes, and comparative taxonomic data to clarify species boundaries. As *Drosophila* parasitoids are often maintained in laboratory cultures, it is also possible to use mating experiments to explore species boundaries under the paradigm of the biological species concept (Seehausen et al., 2020).

DROP as a taxonomic tool

DROP offers an empirical platform for species discovery and a useful tool for taxonomic research. The fact that the number of BINs reported here exceeds the number of described species (Table S1, Figure S3) highlights the need for taxonomic work. But such work cannot proceed on the basis of BINs or barcodes, but requires integrative taxonomic approach employing a combination of molecular and morphological data. Describing new species on the sole basis of a barcode or BIN, without the benefit of independent character data, should, in general, be avoided (Meier et al., 2021). It risks creating nomenclatural synonymy if it is later determined that a sequence can be attributed to a specimen that bears a valid, available name. Moreover, BINs are based on distance analyses which, by definition, are incompatible with diagnoses per se (Ferguson, 2002; Prendini et al., 2002; Goldstein & DeSalle, 2011). Therefore, in taxonomic treatments, it is critical to clarify the range of applicability of a given BIN and its overlap with a taxonomic name (see example in Figure 1). DROP allows cross-linking between studies and therefore provides researchers with valuable tools for

taxonomic revisions, including the means of discovery, corroboration, and description of new species.

How to use DROP to ensure cross-linking between studies and reliable molecular identification?

Public genetic databases have adopted a longstanding convention in treating undetermined OTUs and sequences, referring to provisional species with numbers, as for example "sp. 1", and these are rarely linked to vouchers. For OTUs designated as provisional species, DROP enables cross-indexing of specimens, sequences and references between any studies (ecological, taxonomic, evolutionary, genetic, etc). The best way to ensure cross-linking is depositing a voucher in DROP, together with a sequence or genome from the same individual (or individual from the same strain or series). For example, one can write:

Provisional species "drop_Gan1_sp.1" refers to voucher USNMENT01557320 deposited in the USNM, Washington DC, COI sequence (DROP sequence_id: 2, BOLD Process ID: DROP143-21), 28SD1 sequence (DROP sequence_id: 289), and 28SD2 sequence (DROP sequence_id: 303).

Similarly, laboratory strains can be reported in the same way, just adding the DROP lab strain_id. It is important to periodically recheck identification of laboratory strains as cultures are easily cross-contaminated, and deposit vouchers of laboratory

strains associated with experiments to DROP. In the future, when e.g. "drop_Gan1_sp.1" is described as a new species with a formal specific epithet, DROP curator will update the species status and holotype information while keeping this provisional species name as an informal "synonym."

A weaker and thus much less preferred way of cross-linking is to state in the study that the identification of organisms was performed based on molecular identification match of a sequence to DROP sequences. This is the only available option for environmental DNA studies. For example, one can write:

Provisional species "drop_Gan1_sp.1" was identified based on 99.9% blast match of COI to DROP sequence_id: 2 (BOLD Process ID: DROP143-21).

DROP deposition in Zenodo allows referencing of DROP either through general doi (the doi we use throughout this paper), which takes the user always to the latest database version, or through a doi specific to DROP version. When referencing DROP please primarily cite this paper, but for reproducibility it is also good practice to include doi of the specific DROP version used.

There are two basic ways of molecular identification which should ideally be used in combination: sequence matching (blast), and tree-building methods which investigate membership to a cluster. Further, there are a number of decisions to be made with each method, concerning locus (or loci) and thresholds. DROP leaves these decisions up to the users, only provides raw sequences or links to them. Practically, the

choice of loci is currently mostly limited to COI, but in the future it is likely that molecular identifications will be based on multiple loci or whole genomes. Over time we will also get a better idea about what thresholds are more appropriate than a fixed 2% cut off. For rarer parasitoid genera which attack also other hosts besides *Drosophila* (e.g. *Opius*, or *Spalangia* wasps) we suggest caution in the identification using only DROP sequences as DROP does not include all sequences from these genera, but just from species which are already known to attack *Drosophila*.

From molecular mechanisms to ecosystem structure

The use of molecular tools in insect biodiversity studies has gradually expanded from barcoding single individuals to metabarcoding large environmental samples representing entire food webs (Jeffs et al., 2020; Littlefair et al., 2016). *Drosophila* and their parasitoids are among the few systems that currently allow us to explore thoroughly the mechanisms of species interactions at scales ranging from the molecular to the ecological. Here, we highlight two examples where information compiled in DROP enables the study of the *Drosophila*-parasitoid system across multiple levels of biological organization:

DROP includes a DNA reference library of Australian *Drosophila* parasitoids (dataset: DS-AUSPTOID dx.doi.org/10.5883/DS-AUSPTOID) that connects laboratory experiments and field research. Molecular vouchers of both hosts and parasitoids were collected along altitudinal gradients in the rainforest of northern Queensland, Australia (Jeffs et al., 2021). With this DNA reference library, researchers can detect interactions between

546 *Drosophila* and their parasitoids using PCR-based approaches and parasitized pupae
547 (Hrcek & Godfray, 2015; Jeffs et al., 2020). Surveying host-parasitoid interactions in this
548 way will improve our understanding of how environmental change alters the structure
549 of host-parasitoid networks (Morris et al., 2014; Staniczenko et al., 2017; Tylianakis et
550 al., 2007) by accelerating data collection in the field. In addition, JH established lab
551 cultures of both hosts and their parasitoids from the same Australian sampling sites with
552 the aim of conducting laboratory experiments (e.g. Thierry et al., 2021). Molecular
553 vouchers of the lab strains were then submitted to DROP as a reference database
554 (datasets: DS-LABS dx.doi.org/10.5883/DS-LABS) to ensure that criteria for species
555 determination were applied consistently—and will continue to be applied consistently—
556 between the natural community studies and the laboratory experiments.

557 The presence of a foundational DNA reference library and species catalogue in
558 DROP will enable the process of exploring parasitoid biodiversity to become more
559 efficient. For example, DROP includes molecular vouchers from *Drosophila* parasitoids
560 that were collected across seasons and along latitudinal gradients in the eastern United
561 States (Lue et al., 2016, 2018). These data proved to be extremely useful for identifying
562 species in a more recent exploration of native parasitoid biodiversity across North
563 America (e.g., Abram et al., 2020). There are additional uses for DROP: curated
564 specimen collections may be used to document species distributions, phenology,
565 understand micro-evolutionary patterns, observe the effects of climate change, and
566 detect and track biological invasions (Funk, 2018; Schilthuizen et al., 2015; Tarli et al.,
567 2018).

568

569 ***Taxonomic accuracy for biocontrol studies***

570 Unfortunately, the history of biological control includes many examples of
571 misidentifications that have resulted in failures to employ or establish the expected
572 control agent, thus hindering eventual success (Buffington et al., 2018; Rosen, 1986;
573 Huffaker et al. 1962). In the context of biological control research on *Drosophila* pest
574 species, a simple, reliable, and rapid identification tool for their natural enemies is
575 essential (Wang et al. 2020b). By anchoring the criteria for determining identities of
576 organisms being considered for biological control programs, DROP annotation enables
577 the direct examination of centers of origin for parasitoid species, their co-occurrence
578 with natural enemies, and the optimal timing for potential introductions of such
579 enemies (Abram et al., 2020; Daane et al., 2016; Girod et al., 2018a and b; Kimura, 2015;
580 Mitsui et al., 2007). Because most sequences from DROP are already vetted for
581 reliability, they can be used to identify biological control agents rapidly, before or after
582 being brought into quarantine facilities for safety and efficacy testing. This will decrease
583 the risk of non-target ecological impacts arising from misidentifications and facilitate
584 regulatory review for releases of effective and specific natural enemies.

585 In addition to species identification, reference sequences from DROP may be used as
586 a starting point to create species-specific primers for the accurate identification of
587 parasitoids, design multiplex PCR assays that rapidly distinguish species in natural or
588 agricultural ecosystems (Ye et al., 2017), and apply high-throughput molecular
589 identification diagnostics (Fagan-Jeffries et al., 2018).

590

591 ***Long-term molecular voucher preservation***

592 During the curation of DROP, we found that holotype specimens were missing from
593 museums for several iconic *Drosophila* parasitoid species: *Asobara tabida* (Nees von
594 Esenbeck), *Leptopilina clavipes* (Hartig), and *Leptopilina longipes* (Hartig). This is not
595 uncommon and impedes future taxonomic revisions regardless of whether or not
596 molecular data are used. To avoid contributing to this problem, DROP uses museums as
597 depositories for ensuring that sequenced vouchers of both described species and
598 provisional species are permanently stored. In order to stabilize nomenclature, we
599 further advocate the designation of neotypes (a replacement specimen for a missing
600 holotype or type series) that have museum-vouchered DNA barcodes and additional
601 genomic extractions in storage.

602 Natural history museums are designed to maintain vouchers (including types) for
603 long-term preservation, and increasingly they implement institutionalized workflows
604 that link DNA sequences to specimens and specimen metadata (Prendini et al., 2002).
605 We strongly encourage the deposition of voucher specimens from field surveys and
606 experimental studies in museum collections, as has been urged by the Entomology
607 Collections Network (ECN) and required in many PhD programs. No matter how quickly
608 new molecular techniques are developed or refined, there is no substitute for a reliable
609 database of voucher specimens when it comes to ensuring the repeatability of biological
610 research (Funk et al., 2005; Lendemer et al., 2020).

611 Our results show that species richness of the parasitic wasps that attack *Drosophila*
612 is severely underestimated, and only a fraction of them have been described. In DROP,
613 38% of the OTUs are provisional species, and more than 46% of the named OTUs have
614 synonyms. Remarkably, *Leptopilina heterotoma*, one of the world's most studied
615 parasitoids, has more than 20 synonyms! As is generally the case, the rate of species
616 description and revision of *Drosophila* parasitoids lags far behind that with which
617 molecular sequence data are generated. Ensuring a consistent application of OTU
618 recognition is therefore essential. With DROP, researchers may ensure consistency in
619 their application of scientific names, and that those names are valid, making the
620 daunting process of describing *Drosophila* parasitoids more accurate and efficient. In
621 addition to the collection of physical museum resources, a central role taxonomists play
622 in DROP and its curation is that of fostering better integration of taxonomy with
623 experimental and biodiversity research. Our intention is to perpetuate DROP beyond
624 this introductory publication. We hope that experts in all areas of *Drosophila*-parasitoid
625 biology and related fields will join us in this effort.
626
627 ***Conclusion***

628 Taxonomic confusion presents many obstacles in experimental and biodiversity
629 studies. One way of addressing this impediment is to provide a reliable DNA library with
630 traceable vouchers (Astrin et al., 2013). Compared to BOLD and GenBank, DROP is a
631 small database that provides some advantages over an immense genetic database. For
632 example, it is easier for the research community to have direct communication amongst

633 themselves, when there is a strong focus on a few specific taxa (Weigand et al., 2019). A
634 good database has to maintain good quality of molecular data, but even more
635 challenging is to maintain quality of identification from different sources (Fontes et al.,
636 2021). In a big database, setting up a universal standard that satisfied all the taxa and
637 researchers desires is particularly challenging. The curated nature of DROP will allow us
638 to make strong rules to govern this data and assure users of its fidelity. While GenBank
639 and BOLD each perform some amount of curation, it could be difficult to agree on
640 curators for the whole range of animal and plant species catalogued there. We
641 developed DROP as a resource and platform for gathering and sharing reliable genomic
642 sequence data for *Drosophila* parasitoids. We hope it will serve as a model for
643 researchers working with organisms which present similar difficulties. While compiling
644 DROP, we found that the high number of provisional *versus* named OTUs suggests that
645 the diversity of parasitic wasps attacking *Drosophila* is greatly underestimated. With this
646 in mind, DROP represents the start of an important knowledge base that will strengthen
647 future studies of natural host-parasitoid interactions, population dynamics, biocontrol,
648 and the impact of climate change on biodiversity and ecosystem services.

649

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References

Abram, P. K., Mcpherson, A. E., Kula, R., Hueppelsheuser, T., Perlman, S. J., Curtis, C. I., Fraser, J. L., … Buffington, M. (2020). New records of *Leptopilina*, *Ganaspis*, and *Asobara* species associated with *Drosophila suzukii* in North America, including detections of L. japonica and G. brasiliensis. *Journal of Hymenoptera Research*, 78, 1-17, https://doi.org/10.3897/jhr.78.55026

Astrin, J. J., Zhou, X., & Misof, B. (2013). The importance of biobanking in molecular taxonomy, with proposed definitions for vouchers in a molecular context. *ZooKeys*, 365(SPEC.ISSUE), 67–70. https://doi.org/10.3897/zookeys.365.5875

Baker, C. C. M., Bittleston, L. S., Sanders, J. G., & Pierce, N. E. (2016). Dissecting host-associated communities with DNA barcodes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1702). https://doi.org/10.1098/rstb.2015.0328

Bergsten, J., Bilton, D. T., Fujisawa, T., Elliott, M., Monaghan, M. T., Balke, M., Hendrich, … Vogler, A. P. (2012). The effect of geographical scale of sampling on DNA barcoding. *Systematic Biology,* 61 (5), 851-869. https://doi.org/10.1093/sysbio/sys037

Blaimer, B. B., Gotzek, D., Brady, S. G., & Buffington, M. (2020). Comprehensive phylogenomic analyses re-write the evolution of parasitism within cynipoid wasps. *BMC Ecology and Evolution*, 20 (155). https://doi.org/10.1186/s12862-020-01716-2

Brower, A. V. Z., & DeSalle, R. (2002). Patterns of mitochondrial versus nuclear DNA sequence divergence among nymphalid butterflies: The utility of wingless as a source of characters for phylogenetic inference. *Insect Molecular Biology*, 7 (1), 73-82. https://doi.org/10.1046/j.1365-2583.1998.71052.x

Buffington, M., &Forshage, M. (2016). Redescription of *Ganaspis brasiliensis* (Ihering, 1905), new combination, (Hymenoptera: Figitidae) a natural enemy of the Invasive *Drosophila suzukii* (Matsumura, 1931) (Diptera: Drosophilidae). *Proceedings of the Entomological Society of Washington*, 118(1), 1–13. https://doi.org/10.4289/0013-8797.118.1.1

691 Buffington, M., Talamas, E. J., & Hoelmer, K. A. (2018). Team Trissolcus: Integrating
692 taxonomy and biological control to combat the brown marmorated stink bug.
693 *American Entomologist*, 64 (4), 224–232
694 Carton, Y., Boulétreau, M., van Alphen, J. J. M., & van Lenteren, J. C. (1986). The
695 *Drosophila* parasitic wasps. In Ashburner M, Carson HL, Thompson JN (Eds), *The*
696 *genetics and biology of Drosophila*, (3),348–394.
697 Carton, Y., Haouas, S., Marrakchi, M., & Hochberg, M. (1991). Two competing parasitoid
698 species coexist in sympatry. *Oikos*, 60, 222-230. https://doi.org/10.2307/3544869
699 Condon, M. A., Scheffer, S. J., Lewis, M. L., Wharton, R., Adams, D.C., & Forbes, A. A.
700 (2014). Lethal interactions between parasites and prey increase niche diversity in a
701 tropical community. *Science*, *343*(6176), pp.1240-1244.
702 Daane, K. M., Wang, X.-G., Biondi, A., Miller, B. E., Miller, J. C., Riedl, H., Shearer, P. W.,
703 … Walton, V. M. (2016). First exploration of parasitoids of *Drosophila suzukii* in
704 South Korea as potential classical biological agents. *Journal of Pest Science* 89, 823–
705 835, doi:10.1007/s10340-016-0740-0.
706 Dolphin, K., & Quicke, D. L. J. (2001). Estimating the global incompletely described
707 parasitoid wasps. *Biological Journal Of The Linnean Society*, 73 (3), 279-286,
708 https://doi.org/10.1006
709 Escalante, P., Ibarra-Vazquez, A., & Rosas-Escobar, P. (2010). Tropical montane
710 nymphalids in Mexico: DNA barcodes reveal greater diversity. *Mitochondrial DNA*,
711 21, 30-37, https://doi.org/10.3109/19401736.2010.535527
712 Ferrer-Suay, M., Staverløkk, A., Selfa, J., Pujade-Villar, J., Naik, S., & Ekrem., T. (2018)
713 Nuclear and mitochondrial markers suggest new species boundaries in *Alloxysta*
714 (Hymenoptera: Cynipoidea: Figitidae). Arthropod Systematics & Phylogeny, 76(3),
715 463-473, doi:10.5883/DSALLOXYST
716 Fagan-Jeffries, E. P., Cooper, S. J. B., Bertozzi, T., Bradford, T. M., & Austin, A. D. (2018).
717 DNA barcoding of microgastrine parasitoid wasps (Hymenoptera: Braconidae) using
718 high-throughput methods more than doubles the number of species known for
719 Australia. *Molecular Ecology Resources*, 18(5), 1132–1143.
720 https://doi.org/10.1111/1755-0998.12904
721 Ferguson, J. W. H. (2002). On the use of genetic divergence for identifying species.
722 Biological Journal of the Linnean Society, 75, 509–16.
723 Forbes, A. A., Bagley, R. K., Beer, M. A., Hippee, A. C., & Widmayer, H. A. (2018).
724 Quantifying the unquantifiable: Why Hymenoptera, not Coleoptera, is the most
725 speciose animal order. *BMC Ecology*, 18(1), 1–11. https://doi.org/10.1186/s12898-
726 018-0176-x
727 Fontes, J. T., Vieire, P. E., Ekrem, T., Soares, P., & Costa, F. O. (2021). BAGS: An
728 automated barcode, audit & grade system for DNA barcode reference libraries.
729 *Molecular Ecology Resources*, 21(2), 573-583. https://doi.org/10.1111/1755-
730 0998.13262
731 Funk, V. A. (2018). Collections-based science in the 21st Century. *Journal of Systematics*
732 *and Evolution*, 56(3), 175–193. https://doi.org/10.1111/jse.12315
733 Funk, V. A., Hoch, P. C., Prather, L. A., & Wagner, W. L. (2005). The importance of
734 vouchers. *Taxon*, 54(1), 127–129. https://doi.org/10.2307/25065309

735 Gariepy, T. D., Bruin, A., Konopka, J., Scott-Dupree, C., Fraser, H., Bon, M. C., & Talamas,
736 E. (2019). A modified DNA barcode approach to define trophic interactions
737 between native and exotic pentatomids and their parasitoids. *Molecular Ecology*,
738 28(2), 456–470. https://doi.org/10.1111/mec.14868
739 Giorgini, M., Wang, X.-G., Wang, Y., Chen, F. S., Hougardy, E. , Zhang, H. M., Chen, Z.
740 Q., … Guerrieri, E. (2019). Exploration for native parasitoids of *Drosophila suzukii* in
741 China reveals a diversity of parasitoid species and narrow host range of the
742 dominant parasitoid. *Journal of Pest Science*, 92(2), 509–522.
743 https://doi.org/10.1007/s10340-018-01068-3
744 Girod, P., Borowiec, N., Buffington, M., Chen, G., Fang, Y., Kimura, M. T., Peris-Felipo, F.
745 J., … Kenis, M. (2018). The parasitoid complex of *D. suzukii* and other fruit feeding
746 *Drosophila* species in Asia. *Scientific Reports*, 8(1), e11839.
747 https://doi.org/10.1038/s41598-018-29555-8
748 Girod, P., Lierhmann, O., Urvois, T., Turlings, T. C. J., Kenis. M., & Haye, T. (2018). Host
749 specificity of Asian parasitoids for potential classical biological control of *Drosophila*
750 *suzukii. Journal of Pest Science* 91,1241–1250, https://doi. doi:10.1007/s10340-
751 018-1003-z
752 Goldstein, P. Z., & DeSalle, R. (2011). Integrating DNA barcode data and taxonomic
753 practice: Determination, discovery, and description. *BioEssays*, 33(2),135-147,
754 https://doi.org/10.1002/bies.201000036
755 Gompert, Z., Forister, M. L., Fordyce, J. A., & Nice, C. C. (2008). Widespread mito-nuclear
756 discordance with evidence for introgressive hybridization and selective sweeps in
757 Lycaeides. *Molecular Ecology*, 17(24), 5231-5244, https://doi.org/10.1111/j.1365-
758 294X.2008.03988.x
759 Grissell, E. (1999). Hymenopteran biodiversity: some alien notions. *American*
760 *Entomologist*, 45,236-244.
761 Hardy, I. C., van Alphen, J. J. M., & Godfray, H. C. J. (1994). Parasitoids: Behavioral and
762 evolutionary ecology. *The Journal of Animal Ecology*, 63(4), 1009-1010,
763 https://doi.org/10.2307/5282
764 Hausmann, A., Haszprunar, G., & Hebert, P. D. N. (2011). DNA barcoding the geometrid
765 fauna of bavaria (Lepidoptera): Successes, surprises, and questions. *PLoS ONE*, 6(2),
766 1–9. https://doi.org/10.1371/journal.pone.0017134
767 Hausmann, A., Miller, S. E., Holloway, J. D., Dewaard, J. R., Pollock, D., Prosser, S. W. J.,
768 & Hebert, P. D. N. (2016). Calibrating the taxonomy of a megadiverse insect family:
769 3000 DNA barcodes from geometrid type specimens (Lepidoptera, Geometridae).
770 *Genome*, 59(9), 671–684. https://doi.org/10.1139/gen-2015-0197
771 Hebert, P. D. N., Ratnasingham, S., & DeWaard, J. R. (2003). Barcoding animal life:
772 Cytochrome c oxidase subunit 1 divergences among closely related species.
773 *Proceedings of the Royal Society B: Biological Sciences*, 270 (Suppl.), 96-99,
774 https://doi.org/10.1098/rsbl.2003.0025
775 Hendrich, L., Morinière, J., Haszprunar, G., Hebert, P. D. N., Hausmann, A., Köhler, F., &
776 Balke, M. (2015). A comprehensive DNA barcode database for Central European
777 beetles with a focus on Germany: Adding more than 3500 identified species to
778 BOLD. *Molecular Ecology Resources*, 15(4), 795-818, https://doi.org/10.1111/1755-

779 0998.12354
780 Hrček, J., & Godfray, H. C. J. (2015). What do molecular methods bring to host-parasitoid
781 food webs? *Trends in Parasitology*, 31(1), 30–35.
782 https://doi.org/10.1016/j.pt.2014.10.008
783 Hrcek, J., Miller, S. E., Quicke, D. L. J., & Smith, M. A. (2011). Molecular detection of
784 trophic links in a complex insect host-parasitoid food web. *Molecular Ecology*
785 *Resources*, 11(5), 786–794. https://doi.org/10.1111/j.1755-0998.2011.03016.x
786 Huffaker, C. B., Kennett, C. E., Finney, G. L. (1962). Biological control of olive scale,
787 Pwrlatoria oleae (Cohree), in California by imported Aphytis maculicornis (Masi)
788 (Hymenoptera: Aphelinidae). *Hilgardia,* 32 (13): 541-636. DOI:
789 10.3733/hilg.v32n13p541
790 Hughes, R. D., Woolcock, L. T. (1976). Aphaereta aotea sp. N. (Hymenoptera:
791 Braconidae), an Alysiine parasite of dung breeding flies. J*ournal of Australian*
792 *Entomological Society*, 15, 191-196.
793 Jeffs, C. T., Terry, J. C. D., Higgie. M., Jandová, A., Konvičková. H., Brown. J. J., Lue. C.-H.,
794 … Lewis, O. T. (2020). Molecular analyses reveal consistent food web structure with
795 elevation in rainforest *Drosophila* - parasitoid communities. *Ecography*, 43, 1-11,
796 https://doi.org/10.1111/ecog.05390
797 Kim-Jo, C., Gatti, J. L., & Poirié, M. (2019). *Drosophila* cellular immunity against
798 parasitoid wasps: A complex and time-dependent process. *In Frontiers in*
799 *Physiology*, https://doi.org/10.3389/fphys.2019.00603
800 Kimura, M. T. (2015). Prevalence of exotic frugivorous *Drosophila* species, *D. simulans*
801 and *D. immigrans* (Diptera: Drosophilidae), and its effects on local parasitoids in
802 Sapporo, northern Japan. *Applied Entomology and Zoology*, 50(4), 509–515.
803 https://doi.org/10.1007/s13355-015-0361-8
804 Kimura, M. T., & Mitsui, H. (2020). *Drosophila* parasitoids (Hymenoptera) of Japan. I*n*
805 *Entomological Science*, 23(4), 359-368, https://doi.org/10.1111/ens.12432
806 Klopfstein, S., Kropf, C., & Baur, H. (2016). Wolbachia endosymbionts distort DNA
807 barcoding in the parasitoid wasp genus Diplazon (Hymenoptera: Ichneumonidae).
808 *Zoological Journal of the Linnean Society*, 177(3), 541–557.
809 https://doi.org/10.1111/zoj.12380
810 Kraaijeveld, A. R., & Godfray, H. C. J. (1997). Trade-off between parasitoid resistance and
811 larval competitive. *Nature*, 389, 278-280, https://doi.org/10.1038/38483
812 Lefèvre, T., De Roode, J. C., Kacsoh, B. Z., & Schlenke, T. A. (2012). Defence strategies
813 against a parasitoid wasp in Drosophila: Fight or flight? *Biology Letters*, 8(2), 230-
814 233, https://doi.org/10.1098/rsbl.2011.0725
815 Lendemer, J., Thiers, B., Monfils, A. K., Zaspel, J., Ellwood, E. R., Bentley, A., LeVan, K., …
816 Aime, M. C. (2020). The extended specimen network: A strategy to enhance US
817 biodiversity collections, promote research and education. *BioScience*, 70(1), 23-30,
818 https://doi.org/10.1093/biosci/biz140
819 Lin, C. P., & Danforth, B. N. (2004). How do insect nuclear and mitochondrial gene
820 substitution patterns differ? Insights from Bayesian analyses of combined datasets.
821 *Molecular Phylogenetics and Evolution*, 30(3), 686-702,
822 https://doi.org/10.1016/S1055-7903(03)00241-0

823 Lin, X., Stur, E., & Ekrem, T. (2015). Exploring genetic divergence in a species-rich genus
824 using 2790 DNA barcodes. *PLoS ONE*, 10(9): e0138993.
825 https://doi.org/10.1371/journal.pone.0138993
826 Littlefair, J. E., Clare, E. L., & Naaum, A. (2016). Barcoding the food chain: From Sanger to
827 high-throughput sequencing1. *Genome*, 59(11), 946–958.
828 https://doi.org/10.1139/gen-2016-0028
829 Lue, C.-H., Borowy, D., Buffington, M. L., & Leips, J. (2018). Geographic and seasonal
830 variation in species diversity and community composition of frugivorous *Drosophila*
831 (Diptera: Drosophilidae) and their *Leptopilina* (Hymenoptera: Figitidae) parasitoids.
832 *Environmental Entomology*, 47(5): 1096-1106. https://doi.org/10.1093/ee/nvy114
833 Lue, C.-H., Driskell, A. C., Leips, J., & Buffington, M. L. (2016). Review of the genus
834 *Leptopilina* (Hymenoptera, Cynipoidea, Figitidae, Eucoilinae) from the Eastern
835 United States, including three newly described species. J*ournal of Hymenoptera*
836 *Research*, 53: 35-76. https://doi.org/10.3897/jhr.53.10369
837 Meiklejohn, K. A., Damaso, N., & Robertson, J. M. (2019). Assessment of BOLD and
838 GenBank – Their accuracy and reliability for the identification of biological
839 materials. *PLoS ONE,* 14(6): e0217084.
840 https://doi.org/10.1371/journal.pone.0217084
841 Meier, R., Blaimer, B., Buenaventura, E., Hartop, E., von Thomas, R., Srivathsan, A., &
842 Yeo, D. (2021) A re-analysis of the data in Sharkey et al.,'s (2021) minimalist
843 revision reveals that BINs do not deserve names, but BOLD Systems needs a
844 stronger commitment to open science. *bioRxiv*.
845 https://doi.org/10.1101/2021.04.28.441626
846 Melk, J. P., & Govind, S. (1999). Developmental analysis of *Ganaspis xanthopoda*, a larval
847 parasitoid of *Drosophila melanogaster*. *Journal of Experimental Biology*, 202, 1885-
848 1896
849 Miller, S. E., Hausmann, A., Hallwachs, W., & Janzen, D. H. (2016). Advancing taxonomy
850 and bioinventories with DNA barcodes. *Philosophical Transactions of the Royal*
851 *Society Biological Sciences*, 371(1702): 20150339. doi: 10.1098/rstb.2015.0339
852 Mitsui, H., van Achterberg, K., Nordlander, G., & Kimura, M. T. (2007). Geographical
853 distributions and host associations of larval parasitoids of frugivorous *Drosophilidae*
854 in Japan. *Journal of Natural History*, 41(25–28), 1731–1738.
855 https://doi.org/10.1080/00222930701504797
856 Moreau, S. J. M., Vinchon, S., Cherqui, A., & Prévost, G. (2009). Components of Asobara
857 venoms and their effects on hosts. *In Advances in Parasitology*, Prévost G (Ed). 70,
858 217-232, https://doi.org/10.1016/S0065-308X(09)70008-9
859 Morris, R. J., Gripenberg, S., Lewis, O. T., & Roslin, T. (2014). Antagonistic interaction
860 networks are structured independently of latitude and host guild. *Ecology Letters*,
861 17(3), 340-349, https://doi.org/10.1111/ele.12235
862 Nappi, A. J., & Carton, Y. (2001). Immunogenetic aspects of the cellular immune
863 response of *Drosophila* against parasitoids. *Immunogenetics*, 52(3–4), 157–164.
864 https://doi.org/10.1007/s002510000272
865 Nomano, F. Y., Kasuya, N., Matsuura, A., Suwito, A., Mitsui, H., Buffington ,M.L., &
866 Kimura, M. T. (2017). Genetic differentiation of *Ganaspis brasiliensis*

(Hymenoptera: Figitidae) from East and Southeast Asia. *Applied Entomology and Zoology*, 52(3), 429–437. https://doi.org/10.1007/s13355-017-0493-0

Novotny, V., & Miller, S. E. (2014). Mapping and understanding the diversity of insects in the tropics: Past achievements and future directions. *Austral Entomology*, 53(3), 259–267. https://doi.org/10.1111/aen.12111

O'Grady, P. M., & DeSalle, R. (2018). Phylogeny of the genus *Drosophila*. *Genetics*, 209(1), 1–25. https://doi.org/10.1534/genetics.117.300583

Pentinsaari, M., Ratnasingham, S., Miller, S. E., & Hebert, P. D. N. (2020). BOLD and GenBank revisited – Do identification errors arise in the lab or in the sequence libraries? *PLoS One,* 15(4): e0231814. https://doi.org/10.1371/journal. pone.0231814

Pfeiffer, D. G., Shrader, M. E., Wahls, J. C. E., Willbrand, B. N., Sandum, I., van der Linde, K., Laub, C. A., … Day, E. R. (2019). African Fig Fly (Diptera: Drosophilidae): Biology, expansion of geographic range, and its potential status as a soft fruit pest. *Journal of Integrated Pest Management*, 10(1), 1–8. https://doi.org/10.1093/jipm/pmz018

Prendini, L., Hanner, R., & DeSalle, R. (2002). Obtaining, storing and archiving specimens and tissue samples for use in molecular studies. *In Techniques in Molecular Systematics and Evolution*. https://doi.org/10.1007/978-3-0348-8125-8_11

Prévost, G. (2009). Parasitoids of *Drosophila*. *In Advances in parasitology*. https://doi.org/10.1016/S0065-308X(09)70018-1

Quicke, D. L. J. (2015). The Braconid and Ichneumonid parasitoid wasps: Biology, systematics, evolution and ecology. Wiley-Blackwell, https://doi.org/10.1002/9781118907085

Ratnasingham, S., & Hebert, P. D. N. (2007). BARCODING: bold: The Barcode of Life Data System (http://www.barcodinglife.org). *Molecular Ecology Notes*, 7(3), 355-364, https://doi.org/10.1111/j.1471-8286.2007.01678.x

Ratnasingham, S., & Hebert, P. D. N. (2013). A DNA-based registry for all animal species: the barcode index number (BIN) system. *PLoS ONE,* 8(7): e66213. https://doi.org/10.1371/journal.pone.0066213

Raupach, M. J., Hendrich, L., Kuchler, S. M., Deister, F., Moriniere, J., & Gossner, M. M. (2014). Building-Up of a DNA Barcode Library for true bugs (Insecta: Hemiptera: Heteroptera) of Germany reveals taxonomic uncertainties and surprises. *PLoS ONE*, 9(9), 1–13. https://doi.org/10.1371/journal.pone.0106940

Remsen, J., & O'Grady, P. (2002). Phylogeny of Drosophilinae (Diptera: Drosophilidae), with comments on combined analysis and character support. *Molecular Phylogenetics and Evolution*, 24(2), 249-264, https://doi.org/10.1016/S1055-7903(02)00226-9

Reumer, B, M., van Alphen, J. J. M., & Kraaijeveld, K. (2012). Occasional males in parthenogenetic populations of Asobara japonica (Hymenoptera: Braconidae): Low Wolbachia titer or incomplete coadaptation. *Heredity*, 108(3), 341-346, https://doi.org/10.1038/hdy.2011.82

Rosen, D. (1986). The role of taxonomy in effective biological control programs. *Agriculture, Ecosystems & Environment*, 15(2-3), 121-129. https://doi.org/10.1016/0167-8809(86)90085-X

911 Santos, W. G. N., Fernandes, E. C., Souza, M. M., Guimarães, J. A., & Araujo, E. L. (2016).
912 First record of Eucoilinae (Hymenoptera: Figitidae), parasitoids of African fig fly
913 *Zaprionus indianus* Gupta (Diptera: Drosophilidae), in the Caatinga biome.
914 *Semina:Ciencias Agrarias*, 37(5), 3055–3058. https://doi.org/10.5433/1679-
915 0359.2016v37n5p3055
916 Schilthuizen, M., Vairappan, C. S., Slade, E. M., Mann, D. J., & Miller, J. A. (2015).
917 Specimens as primary data: Museums and "open science." *Trends in Ecology and*
918 *Evolution*, 30(5), 237–238. https://doi.org/10.1016/j.tree.2015.03.002
919 Schlenke, T. A., Morales, J., Govind, S., & Clark, A. G. (2007). Contrasting infection
920 strategies in generalist and specialist wasp parasitoids of *Drosophila melanogaster*.
921 *PLoS Pathogens*, 3(10):e158, https://doi.org/10.1371/journal.ppat.0030158
922 Schindel, D., & Miller, S. E. (2010). Provisional Nomenclature the on-ramp to taxonomic
923 names. In: Polaszek, A. (Ed), *Systema Nature*, 250: The Linnaean Ark. CRC, Boca
924 Raton, 109-115.
925 Seehausen, M. L., Ris, N., Driss, L., Racca, A., Girod, P., Warot, S., Borowiec, N., Tosevski,
926 I., & Kenis, M. (2020). Evidence for a cryptic parasitoid species reveals its suitability
927 as a biological control agent. *Scientific reports*, 10: 19096.
928 https://doi.org/10.1038/s41598-020-76180-5
929 Shokralla, S., Spall, J. L., Gibson, J. F., & Hajibabaei, M. (2012). Next-generation
930 sequencing technologies for environmental DNA research. *In Molecular Ecology*,
931 21(8), 1794-1805, https://doi.org/10.1111/j.1365-294X.2012.05538.x
932 Smith, M. A., Fisher, B. L., & Hebert, P. D. N. (2005). DNA barcoding for effective
933 biodiversity assessment of a hyperdiverse arthropod group: The ants of
934 Madagascar. *Philosophical Transactions of the Royal Society Biological Sciences*,
935 360(1462), 1825-1834, https://doi.org/10.1098/rstb.2005.1714
936 Smith, M. A., Fernandez-Triana, J. L., Eveleigh, E., Gomez, J., Guclu, C., Hallwachs, W.,
937 Hebert. P. D. N., … Zaldivar-Riveron, A. (2013). DNA barcoding and the taxonomy of
938 Microgastrinae wasps (Hymenoptera, Braconidae): impacts after 8 years and nearly
939 20000 sequences. *Molecular Ecology Resource*s, 13, 168-276,
940 https://doi.org/10.1111/1755-0988.12038
941 Staniczenko, P. P. A., Reed-Tsochas, F., Lewis, O. T., Tylianakis, J. M., Albrecht, M.,
942 Coudrain, V., & Klein, A. M. (2017). Predicting the effect of habitat modification on
943 networks of interacting species. *Nature Communications*, 8, 792,
944 https://doi.org/10.1038/s41467-017-00913-w
945 Tarli, V. D., Grandcolas, P., & Pellens, R. (2018). The informative value of museum
946 collections for ecology and conservation: A comparison with target sampling in the
947 Brazilian Atlantic forest. *PLoS ONE*, 13(11): e0205710.
948 https://doi.org/10.1371/journal.pone.0205710
949 Terry, J. C. D., Chen, J., & Lewis, O. T. (2021). The effect of natural enemies on the
950 coexistence of competing species - an empirical test using Bayesian modern
951 coexistence theory. *bioRxiv*: https://doi.org/10.1101/2020.08.27.270389
952 Thierry, M., Pardikes, N. A., Lue, C.-H., Lewis, O. L., & Hrcek, J. (2021). Experimental
953 warming influences species abundances in a *Drosophila* host community through
954 direct effects on species performance rather than altered competition and

parasitism. *PLoS ONE*, 16(2): e0245029. https://doi.org/10.1371/journal.pone.0245029

Troudet, J., Vignes-Lebbe, R., Grandcolas, P., & Legendre, F. (2018). The increasing disconnection of primary biodiversity data from specimens: How does it happen and how to handle it? *Systematic Biology*, 67(6), 1110–1119. https://doi.org/10.1093/sysbio/syy044

Tylianakis, J. M., Tscharntke, T., & Lewis, O. T. (2007). Habitat modification alters the structure of tropical host-parasitoid food webs. *Nature*, 445(7124), 202–205. https://doi.org/10.1038/nature05429

Wachi, N., Nomano, F. Y., Mitsui, H., Kasuya, N., & Kimura, M. T. (2015). Taxonomy and evolution of putative thelytokous species of Leptopilina (Hymenoptera: Figitidae) from Japan, with description of two new species. *Entomological Science*, 18(1), 41–54. https://doi.org/10.1111/ens.12089

Wang, X.-G., Biondi, A., & Daane, K. M. (2020). Functional responses of three candidate Asian larval parasitoids evaluated for classical biological control of *Drosophila suzukii. Journal of Economic Entomology*, 113(1): 73–80. doi: 10.1093/jee/toz265

Wang, X.-G., Biondi, A., Nance. A. N., Zappalà, L., Hoelmer, K. A., & Daane, K. M. (2021). Assessment of Asobara japonica as a potential biological control agent for the spotted wing drosophila, Drosophila suzukii. *Entomologia Generalis (In Press)* doi: 10.1127/entomologia/2020/1100

Wang, X.-G., Lee, J., Daane, K.M., Buffington, M., & Hoelmer, K. A. (2020). Biological control of *Drosophila suzukii*. *CAB Reviews* 54, 10.1079/PAVSNNR202015054

Weigand, H., Beermann, A. j., Čiampor, F., Costa, F. O., Csabai, Z., Duarte, S., Geiger, M. F., … Ekrem, T. (2019). DNA barcode reference libraries for the monitoring of aquatic biota in Europe: Gap-analysis and recommendations for future work. *Science of The Total Environment.* 687(15), 499-254. https://doi.org/10.1016/j.scitotenv.2019.04.247

Xiao, J. H., Wang, N. X., Murphy, R. W., Cook, J., Jia, L. Y., & Huang, D. W. (2012). Wolbachia infection and dramatic intraspecific mitochondrial DNA divergence in a fig wasp. *Evolution*, 66, 1907-1916, https://doi.org/10.1111/j.1558-5646.2011.01561.x

Xie. J., Tiner, B., Vilchez, I., & Mateos, M. (2011). Effect of the *Drosophila* endosymbiont *Spiroplasma* on parasitoid wasp development and on the reproductive fitness of wasp-attacked fly survivors. *Evolutionary Ecology*, 25, 1065-1079, https://doi.org/10.1007/s10682-010-9453-7

Xie, J., Winter, C., Winter, L., & Mateos, M. (2015). Rapid spread of the defensive endosymbiont *Spiroplasma* in *Drosophila hydei* under high parasitoid wasp pressure. *FEMS Microbiology Ecology*, 91(2), 1-11, https://doi.org/10.1093/femsec/iu017

Yassin, A. (2013). Phylogenetic classification of the Drosophilidae Rondani (Diptera): The role of morphology in the postgenomic era. *Systematic Entomology*, https://doi.org/10.1111/j.1365-3113.2012.00665.x

Yassin, A., & David, J. R. (2010). Revision of the Afrotropical species of *Zaprionus* (Diptera, Drosophilidae), with descriptions of two new species and notes on

internal reproductive structures and immature stages. *ZooKeys,* 51, 33-72, https://doi.org/10.3897/zookeys.51.380

Ye, Z., Vollhardt, I. M. G., Girtler, S., Wallinger, C., Tomanovic, Z., & Traugott, M. (2017). An effective molecular approach for assessing cereal aphid-parasitoid-endosymbiont networks. *Scientific Reports*, 7(1), 1–12. https://doi.org/10.1038/s41598-017-02226-w

Yu, D. S. K., 2016, Global index for Ichneumonoidea. Last updated October 22, 2016 https://web.archive.org/web/20161022093945/http:/ichneumonoidea.name/global.php

Data Accessibility

The DROP database is freely accessible at Zenodo depository (http://doi.org/10.5281/zenodo.4519656). Sequences from GenBank and BOLD, all compiled in BOLD, DROP project, DS-DROPAR dataset dx.doi.org/10.5883/DS-DROPAR. New sequences have been deposited in BOLD, DROP project (datasets: DS-LABS dx.doi.org/10.5883/DS-LABS and DS-AUSPTOID dx.doi.org/10.5883/DS-AUSPTOID).

Author Contributions

The initial project idea was originated by C-HL, MLB, JH, MM, TS, JV, SG, and PPAS. Molecular work was conducted by C-HL, SS, ML, AJ, and AD. BOLD and GenBank data was harvested by TAE and C-HL. Figures were made by AL and C-HL. Laboratory and field sample preparations were conducted by MTK, YC, TS, MM, SG, JV, EG, MG, XW, KM, KMD, PA, NAP, MT, JJB, MP, FMJ, WDT, JSD, BW, OTL, PPAS, JL and AL. Taxonomic concepts and interpretations were conducted by RRK, MLB, CH-L, PG, and SEM. DROP database was built by JH and C-HL. All authors contributed to review and final revisions of the manuscript, which was written primarily by C-HL, MLB and JH.

Figures:

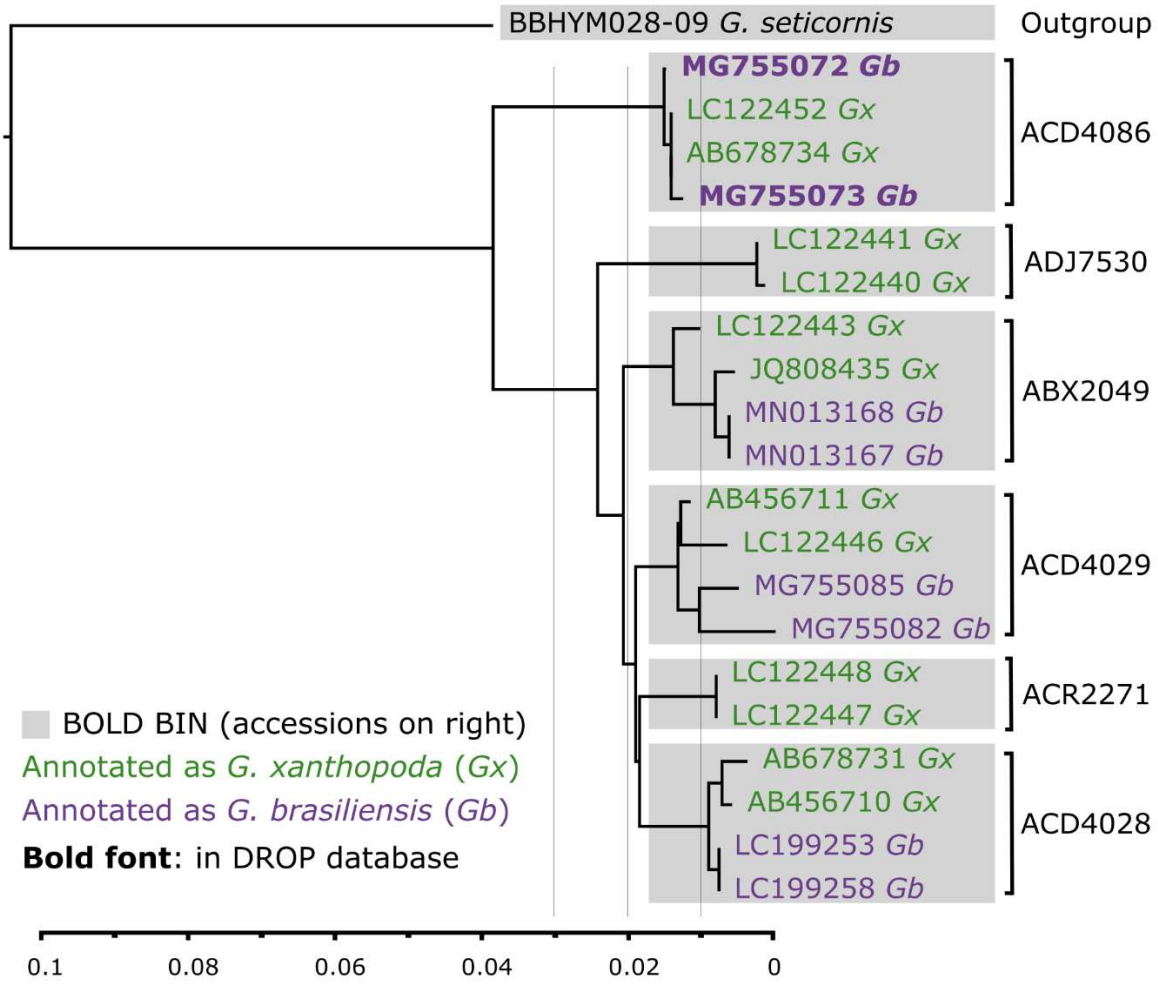

Figure 1: An example of difficulties of molecular identification demonstrated on *Ganaspis xanthopoda* and *G. brasiliensis*. Only two sequences (in bold text) can be reliably used for identification and are included in DROP database. To select the sequences, we searched the BINs associated with the organism's name "*Ganaspis xanthopoda"* (green) or *"Ganaspis brasiliensis"* (purple) in BOLD. From each BIN, two sequences from each species were selected to build a neighbor-joining tree (bottom axis indicated % genetic divergence). There was a total of 6 BINs (gray boxes) in this sequence complex. Of these, 4 BINs contained both species names and without examination of vouchers, identification would be impossible. In DROP, vouchers from two sequences, **MG755073** and **MG755072**, were deposited in CNR-IPSP (Table S2), examined by taxonomists and identified as *G. brasiliensis*. These two COI sequences can now be used to reliably identify *G. brasiliensis*. For *G. xanthopoda,* there were no available vouchers or reliable sequences that passed DROP standards to use for identification. Species delimitation between *G. brasiliensis* and *G. xanthopoda* is convoluted, varies according to arbitrary % genetic divergence (gray vertical lines), and needs an integrative taxonomic revision.

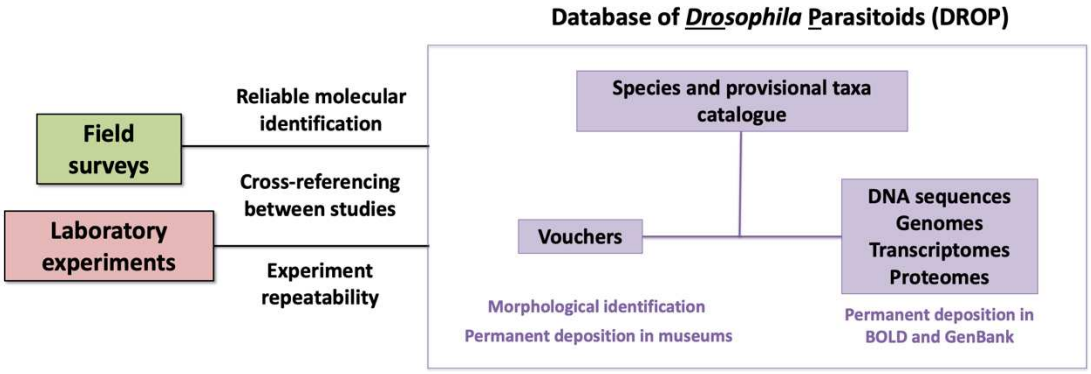

Figure 2: Concept of a centralized, vetted, curated database for *Drosophila* Parasitoids (DROP) we developed. First, we provide a species and provisional species catalog with correct taxonomy. Second, to provide a reliable genetic reference library, we link genetic data (DNA sequences, genomes, transcriptomes, proteomes) to a voucher connected to the species catalog. Third, we link the two primary sources of data (field surveys and laboratory experiments) by requiring a permanent deposition of vouchers and sequences in order to be included in DROP.

Tables:

Table 1: List of species and provisional species included in DROP. For additional taxonomic details, see DROP.

Superfamily	Family	Genus	Species_Name	Author
Chalcidoidea	Encyrtidae		*drop_Cha2_sp12*	
Chalcidoidea	Encyrtidae	*Tachinaephagus*	*drop_ IR1_sp41*	Kimura
Chalcidoidea	Encyrtidae	*Tachinaephagus*	*drop_BG1_sp42*	Kimura
Chalcidoidea	Encyrtidae	*Tachinaephagus*	*zealandicus*	Ashmead 1904
Chalcidoidea	Pteromalidae		*drop_Pte69_sp11*	
Chalcidoidea	Pteromalidae	*Pachycrepoideus*	*vindemmiae*	(Rondani, 1875)
Chalcidoidea	Pteromalidae	*Spalangia*	*drop_IR1_sp38*	Kimura
Chalcidoidea	Pteromalidae	*Spalangia*	*drop_NG1_sp39*	Kimura
Chalcidoidea	Pteromalidae	*Spalangia*	*drop_SK1_sp40*	Kimura
Chalcidoidea	Pteromalidae	*Spalangia*	*drosophilae*	Ashmead 1887
Chalcidoidea	Pteromalidae	*Spalangia*	*erythromera*	Foerster 1850
Chalcidoidea	Pteromalidae	*Trichomalopsis*	*dubia*	(Ashmead, 1896)
Chalcidoidea	Pteromalidae	*Trichomalopsis*	*microptera*	(Lindeman, 1887)
Chalcidoidea	Pteromalidae	*Trichomalopsis*	*nigricola*	Boucek

Chalcidoidea	Pteromalidae	*Trichomalopsis*	*sarcophagae*	(Gahan, 1914)
Chalcidoidea	Pteromalidae	*Vrestovia*	*brevior*	Boucek 1993
Chalcidoidea	Pteromalidae	*Vrestovia*	*fidenas*	(Walker, 1848)
Chalcidoidea	Pteromalidae		*drop_ PacAtl_sp46*	
Chalcidoidea	Pteromalidae		*drop_ PachyPort_sp45*	
Chalcidoidea			*drop_ CH_sp64*	
Cynipoidea	Figitidae	*Ganaspis*	*brasiliensis*	(Ihering, 1905)
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gan_sp51*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gan_sp52*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gan_sp53*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gsp1_sp67*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gsp2_sp68*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ Gsp50_sp66*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_ IR1_sp25*	Kimura
Cynipoidea	Figitidae	*Ganaspis*	*drop_ IR2_sp26*	Kimura
Cynipoidea	Figitidae	*Ganaspis*	*drop_Gan1_sp1*	
Cynipoidea	Figitidae	*Ganaspis*	*drop_TK1_sp27*	Kimura
Cynipoidea	Figitidae	*Ganaspis*	*hookeri*	Craword 1913
Cynipoidea	Figitidae	*Ganaspis*	*mahensis*	Kieffer 1911
Cynipoidea	Figitidae	*Ganaspis*	*mellipes*	(Say, 1826)
Cynipoidea	Figitidae	*Ganaspis*	*mundata*	Forster 1869
Cynipoidea	Figitidae	*Ganaspis*	*seticornis*	(Hellen, 1960)
Cynipoidea	Figitidae	*Ganaspis*	*tenuicornis*	Kieffer 1904
Cynipoidea	Figitidae	*Ganaspis*	*xanthopoda*	(Ashmead, 1896)
Cynipoidea	Figitidae	*Kleidotoma*	*bicolor*	(Giraud, 1860)
Cynipoidea	Figitidae	*Kleidotoma*	*dolichocera*	Thomson 1877
Cynipoidea	Figitidae	*Kleidotoma*	*drop_TK1_sp28*	Kimura
Cynipoidea	Figitidae	*Kleidotoma*	*filicornis*	(Cameron, 1889)
Cynipoidea	Figitidae	*Kleidotoma*	*icarus*	(Quinlan, 1964)
Cynipoidea	Figitidae	*Kleidotoma*	*psiloides*	Westwood 1833
Cynipoidea	Figitidae	*Kleidotoma*	*tetratoma*	(Hartig, 1841)
Cynipoidea	Figitidae	*Leptolamina*	*drop_Fig64_sp5*	
Cynipoidea	Figitidae	*Leptolamina*	*drop_Lmn_sp6*	
Cynipoidea	Figitidae	*Leptolamina*	*drop_TK1_sp29*	Kimura
Cynipoidea	Figitidae	*Leptolamina*	*gressitti*	Yoshimoto & Yasumatsu 1965
Cynipoidea	Figitidae	*Leptolamina*	*papuensis*	Yoshimoto 1963
Cynipoidea	Figitidae	*Leptolamina*	*ponapensis*	Yoshimoto 1962
Cynipoidea	Figitidae	*Leptolamina*	*seychellensis*	(Kieffer, 1911)

Cynipoidea	Figitidae	*Leptopilina*	*atraticeps*	(Kieffer, 1911)
Cynipoidea	Figitidae	*Leptopilina*	*australis*	(Belizin, 1966)
Cynipoidea	Figitidae	*Leptopilina*	*boulardi*	(Barbotin, Carton & Kelner-Pillault, 1979)
Cynipoidea	Figitidae	*Leptopilina*	*clavipes*	(Hartig, 1841)
Cynipoidea	Figitidae	*Leptopilina*	*cupulifera*	(Kieffer, 1916)
Cynipoidea	Figitidae	*Leptopilina*	*decemflagella*	Lue & Buffington 2017
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp54*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp55*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp56*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp57*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp58*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp59*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp60*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp61*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_ Lep_sp62*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_BG1_sp34*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*drop_Fig059_sp4*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_Fig124_sp2*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_Fig58_sp3*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_IR1_sp30*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*drop_NG1_sp33*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*drop_SK1_sp35*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*drop_STL_sp7*	
Cynipoidea	Figitidae	*Leptopilina*	*drop_TK2_sp31*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*drop_TK3_sp32*	Kimura
Cynipoidea	Figitidae	*Leptopilina*	*fimbriata*	(Kieffer, 1901)
Cynipoidea	Figitidae	*Leptopilina*	*freyae*	Allemand & Nordlander 2002
Cynipoidea	Figitidae	*Leptopilina*	*guineaensis*	Allemand & Nordlander 2002
Cynipoidea	Figitidae	*Leptopilina*	*heterotoma*	(Thomson, 1862)
Cynipoidea	Figitidae	*Leptopilina*	*japonica japonica*	Novkovic & Kimura 2011
Cynipoidea	Figitidae	*Leptopilina*	*lasallei*	Buffington & Guerrieri 2020
Cynipoidea	Figitidae	*Leptopilina*	*leipsi*	Lue & Buffington 2018
Cynipoidea	Figitidae	*Leptopilina*	*lonchaeae*	(Cameron, 1912)
Cynipoidea	Figitidae	*Leptopilina*	*longipes*	(Hartig, 1841)
Cynipoidea	Figitidae	*Leptopilina*	*mahensis*	(Kieffer, 1911)

Cynipoidea	Figitidae	*Leptopilina*	*maia*	Lue & Buffington 2016
Cynipoidea	Figitidae	*Leptopilina*	*maria*	(Girault, 1930)
Cynipoidea	Figitidae	*Leptopilina*	*orientalis*	Allemand & Nordlander 2002
Cynipoidea	Figitidae	*Leptopilina*	*pacifica*	Novkovic & Kimura 2011
Cynipoidea	Figitidae	*Leptopilina*	*rufipes*	(Cameron, 1908)
Cynipoidea	Figitidae	*Leptopilina*	*rugipunctata*	(Yoshimoto, 1962)
Cynipoidea	Figitidae	*Leptopilina*	*ryukyuensis*	Novkovic & Kimura 2011
Cynipoidea	Figitidae	*Leptopilina*	*tokioensis*	Wachi & Kimura 2015
Cynipoidea	Figitidae	*Leptopilina*	*tsushimaensis*	Wachi & Kimura 2015
Cynipoidea	Figitidae	*Leptopilina*	*victoriae*	Nordlander 1980
Cynipoidea	Figitidae	*Rhoptromeris*	*heptoma*	(Hartig, 1840)
Cynipoidea	Figitidae	*Rhoptromeris*	*nigriventris*	Nordlander 1978
Cynipoidea	Figitidae	*Rhoptromeris*	*rufiventris*	(Giraud, 1860)
Cynipoidea	Figitidae	*Rhoptromeris*	*villosa*	(Hartig, 1840)
Cynipoidea	Figitidae		*drop_Lg500_sp43*	
Ichneumonoidea	Braconidae	*Alysia*	*drop_SP1_sp24*	Kimura
Ichneumonoidea	Braconidae	*Aphaereta*	*aotea*	Hughes & Woolcock 1976
Ichneumonoidea	Braconidae	*Aphaereta*	*drop_SP1_sp15*	Kimura
Ichneumonoidea	Braconidae	*Aphaereta*	*drop_TK1_sp13*	Kimura
Ichneumonoidea	Braconidae	*Aphaereta*	*drop_TM1_sp14*	Kimura
Ichneumonoidea	Braconidae	*Aphaereta*	*minuta*	(Nees, 1811)
Ichneumonoidea	Braconidae	*Aphaereta*	*pallipes*	(Say, 1829)
Ichneumonoidea	Braconidae	*Aphaereta*	*scaptomyzae*	Fischer 1966
Ichneumonoidea	Braconidae	*Areotetes*	*striatiferus*	Li & van Achterberg 2013
Ichneumonoidea	Braconidae	*Areotetes*	*carinuliferus*	Li & van Achterberg 2013
Ichneumonoidea	Braconidae	*Asobara*	*ajbelli*	Berry 2007
Ichneumonoidea	Braconidae	*Asobara*	*albiclava*	Berry 2007
Ichneumonoidea	Braconidae	*Asobara*	*antipoda*	(Ashmead, 1900)
Ichneumonoidea	Braconidae	*Asobara*	*bactrocerae*	(Gahan, 1952)
Ichneumonoidea	Braconidae	*Asobara*	*brevicauda*	van Achterberg & Guerrieri 2016
Ichneumonoidea	Braconidae	*Asobara*	*citri*	(Fischer, 1963)
Ichneumonoidea	Braconidae	*Asobara*	*drop_KG1_sp16*	Kimura
Ichneumonoidea	Braconidae	*Asobara*	*drop_NG1_sp17*	Kimura
Ichneumonoidea	Braconidae	*Asobara*	*drop_SK2_sp20*	Kimura

Ichneumonoidea	Braconidae	*Asobara*	*drop_SP1_sp18*	Kimura
Ichneumonoidea	Braconidae	*Asobara*	*drop_Sp2_sp19*	Kimura
Ichneumonoidea	Braconidae	*Asobara*	*elongata*	van Achterberg & Guerrieri 2016
Ichneumonoidea	Braconidae	*Asobara*	*gahani*	(Papp, 1969)
Ichneumonoidea	Braconidae	*Asobara*	*japonica*	Belokobylskij 1998
Ichneumonoidea	Braconidae	*Asobara*	*kenyaensis*	Peris-Felipo 2014
Ichneumonoidea	Braconidae	*Asobara*	*leveri*	(Nixon, 1939)
Ichneumonoidea	Braconidae	*Asobara*	*mesocauda*	van Achterberg & Guerrieri 2016
Ichneumonoidea	Braconidae	*Asobara*	*orientalis*	Viereck 1913
Ichneumonoidea	Braconidae	*Asobara*	*persimilis*	(Prince, 1976)
Ichneumonoidea	Braconidae	*Asobara*	*pleuralis*	(Ashmead, 1905)
Ichneumonoidea	Braconidae	*Asobara*	*rossica*	Belokobylskij 1998
Ichneumonoidea	Braconidae	*Asobara*	*rufescens*	(Fˆrster, 1862)
Ichneumonoidea	Braconidae	*Asobara*	*tabida*	(Nees, 1834)
Ichneumonoidea	Braconidae	*Asobara*	*triangulata*	van Achterberg & Guerrieri 2016
Ichneumonoidea	Braconidae	*Asobara*	*turneri*	Peris-Felipo 2014
Ichneumonoidea	Braconidae	*Asobara*	*unicolorata*	van Achterberg & Guerrieri 2016
Ichneumonoidea	Braconidae	*Aspilota*	*albertica*	Berry 2007
Ichneumonoidea	Braconidae	*Aspilota*	*andyaustini*	Wharton 2002
Ichneumonoidea	Braconidae	*Aspilota*	*angusta*	Berry 2007
Ichneumonoidea	Braconidae	*Aspilota*	*concolor*	Nees 1812
Ichneumonoidea	Braconidae	*Aspilota*	*parecur*	Berry 2007
Ichneumonoidea	Braconidae	*Aspilota*	*villosa*	Berry 2007
Ichneumonoidea	Braconidae	*Dinotrema*	*barrattae*	Berry 2007
Ichneumonoidea	Braconidae	*Dinotrema*	*longworthi*	Berry 2007
Ichneumonoidea	Braconidae	*Dinotrema*	*philipi*	Berry 2007
Ichneumonoidea	Braconidae		*drop_Aso_sp8*	
Ichneumonoidea	Braconidae	*Opiognathus*	*pactus*	(Haliday, 1837)
Ichneumonoidea	Braconidae	*Opius*	*bellus*	Gahan 1930
Ichneumonoidea	Braconidae	*Opius*	*cinerariae*	Fischer
Ichneumonoidea	Braconidae	*Opius*	*crenuliferus*	Li & van Achterberg 2013
Ichneumonoidea	Braconidae	*Opius*	*monilipalpis*	Li & van Achterberg 2013
Ichneumonoidea	Braconidae	*Opius*	*ocreatus*	(Papp)
Ichneumonoidea	Braconidae	*Opius*	*pallipes*	Wesmael 1835
Ichneumonoidea	Braconidae	*Opius*	*pteridiophilus*	Wharton & Austin 1990

Ichneumonoidea	Braconidae	*Opius*	*pterus*	Wharton & Austin 1990
Ichneumonoidea	Braconidae	*Opius*	*trimaculatus*	Spinola
Ichneumonoidea	Braconidae	*Opius*	*youi*	Li & van Achterberg 2013
Ichneumonoidea	Braconidae	*Phaenocarpa*	*conspurcator*	(Haliday, 1838)
Ichneumonoidea	Braconidae	*Phaenocarpa*	*drop_ IR1_sp22*	Kimura
Ichneumonoidea	Braconidae	*Phaenocarpa*	*drop_TK1_sp21*	Kimura
Ichneumonoidea	Braconidae	*Phaenocarpa*	*tacita*	Stelfox 1941
Ichneumonoidea	Braconidae	*Phaenocarpa*	*drosophilae*	(Fischer 1975)
Ichneumonoidea	Braconidae	*Tanycarpa*	*bicolor*	(Nees, 1814)
Ichneumonoidea	Braconidae	*Tanycarpa*	*chors*	Belokobylskij 1998
Ichneumonoidea	Braconidae	*Tanycarpa*	*drop_NG1_sp23*	Kimura
Ichneumonoidea	Braconidae	*Tanycarpa*	*punctata*	van Achterberg 1976
Ichneumonoidea	Braconidae		*drop_ Aly_sp47*	
Ichneumonoidea	Braconidae		*drop_ Aly_sp48*	
Ichneumonoidea	Braconidae		*drop_ Aly_sp49*	
Ichneumonoidea	Braconidae		*drop_ Aly_sp50*	
Ichneumonoidea	Braconidae		*drop_ Aly_sp63*	
Ichneumonoidea	Braconidae		*drop_ Aso_sp69*	
Diaprioidea	Diapriidae	*Trichopria*	*anastrephae*	Costa Lima 1940
Diaprioidea	Diapriidae	*Trichopria*	*drop_ BG1_sp37*	Kimura
Diaprioidea	Diapriidae	*Trichopria*	*drop_ Dia70_sp65*	
Diaprioidea	Diapriidae	*Trichopria*	*drop_ Tri_sp44*	
Diaprioidea	Diapriidae	*Trichopria*	*drop_Bdia_sp10*	
Diaprioidea	Diapriidae	*Trichopria*	*drop_Dia127_sp9*	
Diaprioidea	Diapriidae	*Trichopria*	*drop_TK1_sp36*	Kimura
Diaprioidea	Diapriidae	*Trichopria*	*drosophilae*	(Kieffer, 1912)
Diaprioidea	Diapriidae	*Trichopria*	*modesta*	(Ratzeburg, 1848)

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