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Forum

The Global Ant Biodiversity Informatics (GABI) database: synthesizing data on the geographic distribution of ant species (Hymenoptera: Formicidae)

Benoit Guénard (contact author), School of Biological Sciences, The University of Hong Kong, Hong Kong SAR; Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan. E-mail: bguenard@hku.hk

Michael D. Weiser, Department of Biology, University of Oklahoma, OK, 73019, USA.
Kiko Gómez, Castelldefels, Barcelona, Spain.
Nitish Narula & Evan P. Economo, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan.

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Abstract: The global distribution patterns of most vertebrate groups and several plant groups have been described and analyzed over the past few years, a development facilitated by the compilation of important databases. Similar efforts are needed for large insect groups that constitute the majority of global biodiversity. As a result of this lack of information, invertebrate taxa are often left out of both large-scale analyses of biodiversity patterns and large-scale efforts in conservation planning and prioritization. Here, we introduce the first comprehensive global database of ant species distributions, the Global Ant Biodiversity Informatics (GABI) database, based on the compilation of 1.72 million records extracted from over 8811 publications and 25 existing databases. We first present the main goals of the database, the methodology used to build the database, as well as its limitations and challenges. Then, we discuss how different fields of ant biology may benefit from utilizing this tool. Finally, we emphasize the importance of future participation of myrmecologists to improve the database and use it to identify and fill holes in our knowledge of ant biodiversity.

Key words: Formicidae, ants, database, global distribution, species distribution, ecoinformatics, biogeography.

Introduction

Over the past few decades, researchers have generated data sets that describe species distributions and global diversity patterns for several plant and vertebrate groups (e.g., KIER & al. 2005, ORME & al. 2005, BUCKLEY & JETZ 2007, SCHIPPER & al. 2008, PIMM & al. 2014). These efforts in "biodiversity informatics" have facilitated unprecedented understanding of patterns of biodiversity (e.g., KREFT & JETZ 2007), the processes shaping them (e.g., KERKHOFF & al. 2014), and have considerable implications for conservation (JOPPA & al. 2013). While insects represent more than two-thirds of described species (ZHANG 2013), they have been mostly left out of global-scale comprehensive analyses (DINIZ-FILHO & al. 2010, but see FOLEY & al. 2007). Recent attempts, using community-level data and generic distribution records of an ecologically dominant and ubiquitous group, ants (Hymenoptera: For-

micidae), have brought novel insights to macroecological and evolutionary questions with a global perspective (DUNN & al. 2009, WEISER & al. 2010, JENKINS & al. 2011, GUÉNARD & al. 2012, LUCKY & al. 2013). Other projects have considerably improved knowledge on species distributions at various spatial and taxonomic scales including: global scale (e.g., specimen records at ANTWEB 2015), biogeographical regions (e.g., Neotropical: FERNANDEZ & SENDOYA 2004), continents (e.g., Europe: BOROWIEC 2014), countries (e.g., China: GUÉNARD & DUNN 2012, Costa Rica: LONGINO 2010, Fiji: SARNAT & ECONOMO 2012, India: BHARTI & al. 2016, Japan: JAPANESE ANT DATABASE GROUP 2003); or sometimes more specifically on a given taxonomic group (e.g., *Myrmica*: RADCHENKO & ELMES 2010) or on ecological groups (e.g., introduced species: WETTERER 2008). All these efforts provide valuable contributions that focus on specific facets of biodiversity data, but thus far a comprehensive, global accounting of the known distributions of all ant species is still needed.

A long history of myrmecological research has accumulated a tremendous amount of biodiversity data in the form of published literature, museum collections, and specimen record databases. However, the utility of these data for synthetic research has been limited due to its disaggregation and fragmentation. The literature records are scattered across a large number of often obscure and difficult to access publications, some hundreds of years old, not found in normal University libraries, and often published in languages other than English. Moreover, the continued evolution of ant taxonomy means that old literature records need to be curated and reconciled with our latest taxonomic frameworks in order to remain relevant. Even if aggregated these data are undoubtedly incomplete both for described species as well as the large number of yet undescribed species (WARD 2014).

The Anthropocene biodiversity crisis (CORLETT 2015) has created a pressing need for the development of a biodiversity informatics framework that aggregates these diverse data types to understand and close the important geographic (GUÉNARD & al. 2012) and taxonomic gaps (WARD 2014) of species distributions. Such databases can be used to monitor the distribution of known species, provide raw data to accelerate taxonomy and inventory work, and provide tools that will facilitate field research for ecologists and conservation biologists.

Here we introduce the Global Ant Biodiversity Informatics (GABI) database, an attempt to summarize the knowledge of all ant species distributions, and in their aggregate form, geographic patterns of ant biodiversity. We describe the overall goals of the project, the data sources and compilation methodology, the organization of the data, and review some potential scientific uses of the data. The data can be viewed through a custom-built web-mapping interface, antmaps.org (JANICKI & al. 2016). Additional

mechanisms to distribute the data are under development, and pending its completion and full documentation in the literature, we intend for the GABI data to be an open resource available to all. We expect GABI to become an important new tool for biologists for the study and understanding of ant distribution at all taxonomic levels; and open a new era of more rapid and penetrating macroecological, macroevolutionary, and taxonomic investigation of the Formicidae. With this new tool, we hope that ant biologists will gain a better understanding of ant species distributions and use it to accelerate the discovery and description of new taxa and new species distribution records in the mold of what already exists for vertebrate groups like birds.

Goals of the GABI project

Compile all known information on the geographic distribution of all ant species in a single database, including a comprehensive accounting of publications, specimen databases, museum collections, and other collection records.

- Identify erroneous and dubious records that may exist in the literature or other data sources.
- Provide range maps for each species, genus and subfamily, distinguishing native and exotic ranges.
- Provide a first draft of species checklists for all regions of the world.
- Provide the raw material for enhanced biogeographic analysis of ant biodiversity patterns.
- Provide the raw material for integrating ant biodiversity information into global conservation efforts.
- Develop an interactive framework for the continued growth and improvement of the database, with the participation of the global myrmecological research community.

Data sources and compilation methodology

The GABI database includes data from multiple sources in order to cover a large scope of publications, public and private databases and museum specimens (see detailed methodology in Supplements S1-6, as digital supplementary material to this article, at the journal's web pages).

The specific information presented here represents the state of the GABI database on 10 September 2016, however it should be noted that the database is continuously updated so the list becomes more extensive over time.

- Published literature records from 8811 publications have been compiled and represent a wide array of fields, language or print medium. Taxonomic literature was given priority to ensure the completeness of all ant description records. Species checklists (including various books), taxonomic records and community ecology articles were also highly prioritized to ensure the completeness in coverage of local or regional fauna.
- Several online ant databases are available either individually (e.g., ANTWEB 2015) or in aggregating databases (e.g., GBIF 2016, www.gbif.org). A total of 25 databases were extracted, adapted to our database format and incorporated into GABI. A complete list of the databases used is provided in Supplement S2.
- Museum records or personal collections: Non-databased specimens present in museums have occasionally been added as well as specific unpublished information provided by ant biologists. It should be noted that those how-

ever represent a small proportion of our data and are added on the basis of trust of known experts. We do hope that more direct information could be collected in that manner in the future through direct communication with local experts. Toward that end, the release of the website antmaps.org (presented in details in JANICKI & al. 2016) and of the option "Report Data Issue" has facilitated the communication about personal records.

Organization and presentation of the data

Taxonomic information: Taxonomy is an evolving field of biology, and the taxonomic frameworks used for ant biology remain dynamic at all levels (WARD 2007, 2014). One major challenge for the construction of a global database is to ensure that the current taxonomy of the taxa used represents their most updated status. Thanks to tools developed previously (e.g., BOLTON 2014, 2015), taxonomic changes have been kept up to date along the construction of GABI, with continuous synchronization with newly published literature.

To ensure the traceability of every record and of their changes over time, the information relative to the original presentation of the taxon has been kept separately within the database. In a second step the current valid name was updated in separate fields using the community website BOLTON (2015). The validity of each taxonomic combination has been checked manually. This process permits for the correction of species misspelling that could artificially inflate the species richness in a given region. As a result, a total of 38,239 combination pairs of original taxonomic description*valid species names have been retrieved. For instance, records of *Amblyopone pallipes* were changed to *Stigmatomma pallipes* (HALDEMAN, 1844) following taxonomic changes of YOSHIMURA & FISHER (2012), resulting in the pair *Amblyopone pallipes***Stigmatomma pallipes*. It should be noted that several species records (784) have not been found to correspond to any valid species name known and are thus flagged as "UNKNOWN" until being resolved. In some instances, those records correspond to genus epithet dissociated to the species name and forming new invalid species difficult to track.

Geographic information: A major obstacle for global biodiversity databases is variation in the quality of geographic information provided over decades or centuries of collection. Recently collected specimens often have precise geographic information including GPS coordinates, but data collected earlier, usually before the 1990's, did not record this level of geographic accuracy. One solution to this problem is to keep the minimum geographic level of information provided as the unit for geographic information. The minimum geographic level of information provided is a non-standardized unit of geographic information that range in scale from precise GPS coordinates unit to a city name, county, island, provinces (or states or departments) to country. All other geographic information above the minimum geographic level of information provided are preserved and compiled into specific and categorical columns (see in Tab. S1: Country, First level of administrative division, 2nd level of administrative division, island name, latitude, longitude ...). This method allows the preservation of most collection data independently of the geographic quality provided. The limitations here are: minimum geographic information above the coun-

try level; and regions that have been split over history and from which one part cannot be identified clearly. For instance, the state of Mato Grosso in Brazil has been split in 1977 into two separate states (Mato Grosso and Mato Grosso do Sul) and has such all the records reported with the sole mention of Mato Grosso prior to 1977 cannot be assumed to be within the current Mato Grosso state. When entering data, a certain level of knowledge on the political history of the country of first administrative level was acquired to prevent erroneous record placements.

Relationship to other ant biodiversity databases

Several databases relevant to ant ecology, distribution, taxonomy, and / or richness exist and are invaluable resources for the field. Our goal was not to supplant, but rather to both complement and extend these efforts. Although too many myrmecological data efforts exist for us to give a complete accounting here, we briefly highlight some other efforts that are especially relevant to the current project and discuss how GABI complements them.

ANTWEB (2015), developed in 2002, provides valuable information on the species distribution of numerous extant and fossil species of ants globally. AntWeb is essentially a specimen-based database and thus does not include literature records. As of 22 June 2016, AntWeb had accumulated over half a million records from specimens (562,885 specimens). Among other functions, AntWeb also provides a main resource as a digital image library for a majority of valid described species. AntWeb can be described as mostly taxonomy-oriented with a main goal to provide species description and images for all ant species (modern and fossil), while GABI is biogeography-oriented and attempt to provide complete species distribution records for all valid current ant taxa.

In 2007, Dunn and collaborators compiled a database on local ant assemblages based on literature search and a few unpublished datasets. This database compiled information for 2700 sites from 225 studies on overall species richness and abundance (DUNN & al. 2007) but did not include species composition and was limited by the type of sampling used or excluded studies on specific ecological groups (e.g., granivorous ants). Although not initially designed as a community ecology database, GABI can be easily modified to provide information on species richness and composition at different scales, from local to regional scales. However, GABI does not include information on the collecting methods or the specific type of habitat where the record was collected; which might then limit its direct application for community ecology. In general, compared with GABI, the Dunn and collaborators database (2007) is more limited in scope but more stringently curated for its main focus, diversity data at the scale of local communities.

In summary, GABI attempts to provide complete distribution records for all valid ant species and thus differ from previous databases that are either more selective in the type of data used, or focused on specific values (e.g., species richness) independently of the species identity.

Scientific potential of the GABI database

Improving species distribution knowledge and identification: Species identification forms the foundation of ecological and taxonomic studies. Ant identification is a dif-

ficult task which takes often years of training before to be mastered by students and is based on identification keys that, when available, often cover entire bioregions, continents or countries: scales much larger than more localized faunas. For example, the identification of the *Camponotus* species from a sample collected in North Carolina does not require a key including the species also found in California or Montana. As such, biogeography can be used as a filter to discard species that most likely will not be present in the studied region. In contrast, prediction on the presence of a species based on its known occurrence from close regions can facilitate its identification after collection.

One major outcome of GABI is the synthesis of published information and the production of individual maps presenting the distribution for all valid ant taxa, as well as region-based checklists (both automatically generated with latest data through antmaps.org). This facilitates the identification of the collected specimens and to identify rapidly what represents novel information.

Accelerating the publication of new records: As habitat destruction and species extinctions increase over time (DIRZO & al. 2014), the establishment of accurate species distributions, especially for diverse insect groups like ants, should represent a major goal for the fields of biodiversity and conservation. However, the construction of large global databases is limited by the availability and sharing of these data through publications. For ants, most regions of the world do not possess species checklists, or they are partially outdated or incomplete to be used confidently, especially within tropical regions. The lack of species checklists for most regions of the world has an important side effect; it prevents the identification of new species records for a given region. The collection of new species records has been an important aspect of biology to determine the overall distribution of many taxa as seen with birds which represent one of the flagship groups for conservation and biogeography studies, partly due to the impressive amount of data available.

Publications presenting new species records for a given area are relatively easy to write on the spectrum of scientific publications, with now dedicated journals for their publication (e.g., Checklist, Biodiversity Data) and should be largely encouraged as they are at term very important for the understanding of larger scale biogeographic, ecological or evolutionary questions, but also paramount for conservation planning. One major pitfall though is the assertion that the collection of a species represents a new record for the country or province considered, which has to be supported by a tedious work of synthesis and taxonomic update. As a result, while new records could be found at a very fast pace, especially in tropical regions, their publication is slowed by the lack of access to the overall knowledge on species distributions with details on their known range for specific regions. Stating the obvious, new species records sitting in a laboratory cabinet and not being accessible to the rest of the scientific community (through publication or within a database) are not useful and are virtually nonexistent. Publications of those records should then be encouraged and facilitated.

We believe that GABI can enhance the generation of new species records all over the world by providing an important background to the species reported for a given area. As an example, a recent two-weeks survey in Yunnan

province, southern China, allowed the identification of 149 species and of another extra 64 morphospecies (LIU & al. 2015). Among the 149 species identified, 40 have not been reported yet from Yunnan, and 17 represent new records for China according to the GABI database (LIU & al. 2015). This alone represents an increase of nearly 10% and 2% respectively of the known diversity of the ants of Yunnan and China. As such, GABI could be used by ecologists as an important tool to verify the biogeographic accuracy of their identification. This can really speed up the identification process, especially for common species, and present new publication opportunities for newly recorded species. In Hong Kong current work in progress is greatly facilitated by GABI and has allowed the identification of a new subfamily, generic and several species records for Hong Kong and Southeast China (in preparation) and recent publications have used GABI through antmaps.org to identify new records (e.g., SANTOS-SILVA & al. 2016). The update of country species checklists can also be greatly enhanced through the use of GABI. As examples, recent updates for the species checklists of the ants of India (BHARTI & al. 2016), Laos (JAITRONG & al. 2016) or Peru (GUÉNARD & ECONOMO 2015) have greatly benefited from the database; while other species checklists for countries without such publications are currently being developed. These more localized efforts are fundamental to developing a more refined global understanding of species distribution.

Similarly, the detection of new exotic species is an important step for their future potential management. Here, too, by emphasizing individual exotic species distributions, new records could be more easily reported and hopefully will help to establish quick research programs to attempt limiting their spread (HOFFMANN & al. 2009).

Erroneous species identification: Over the last two centuries, many misidentified species records have accumulated either in publications, museums, or databases (see example for plants in GOODWIN & al. 2015). Simply put, species identification is a difficult process. The identification of these errors is an important step as it can include information on the distribution of the valid and non-valid species. Tracking down those mistakes is a challenging effort that can be realized over time by gaining expert opinion through their publications or by direct knowledge sharing after visualization of taxon-specific maps. On the maps produced through the GABI project, the erroneous records are being marked to prevent future misidentifications while in the database a justification for marking a record as erroneous is provided either by citing the publication or the communication information with a given expert stating a record as misidentified. To this point, about 2800 unique species*region records (over 14,200 unique records) have been marked as erroneous or in need of verification (taxon presenting dubious distribution but without specific information to prove or disprove it). Undoubtedly, many more records are in need of correction and we do hope that the ant biologist community as a whole will provide important information to circumscribe the extent of those mistakes. These actions can be easily realized through the visualization of species distribution in antmaps.org and the use of the "Report Data Issue" link with updates available in the following days.

Incorporating ants into global, regional, and local conservation planning: Ants, like many other invertebrates,

have been neglected from most conservation plans (CLARK & MAY 2002, CARDOSO & al. 2011a, b, GERLACH & al. 2014). One of the main conservation tools used to assess species status is the IUCN Species Red List. The Red List is a barometer to assess species vulnerability to extinction; and is used by several conservation grant panels to provide funding for specific projects (CARDOSO & al. 2011b). However, to this point, it can be seen as a broken barometer; pointing towards vertebrates. Arthropods in general, while representing the vast majority of species on Earth have been simply left aside from the IUCN Red List, and only 0.4% of the known insect species have been assessed (GERLACH & al. 2014). For Hymenoptera, 302 species (0.2%) have been assessed (with 151 considered outdated) (GERLACH & al. 2014) on about 150,000 known species described (ZHANG 2013). For ants, 149 species have been assessed in 1996 (IUCN 2013) and one more was added recently (TALAVERA & al. 2014), so about 1% of the known species. Why insects are so largely ignored? The reasons are mainly societal and scientific (see review in DINIZ-FILHO & al. 2010, CARDOSO & al. 2011a, b) with one of the main identified limitation being the Wallacean shortfall (LOMOLINO 2004). The Wallacean shortfall is the lack of geographic information on species distribution, or simply put for conservation purposes, how to protect a species without distribution knowledge?

We believe that by presenting a more accurate and updated status on individual species distribution for all species, GABI should contribute to limit the Wallacean shortfall; and could really push ants forward into conservation planning and IUCN Red List assessment. Of course other potential pitfall might prevent a complete assessment of ants (e.g., Linnean pitfall; see CARDOSO & al. 2011a), but the ease to consider many more species with the new maps produced and access to the database, should be largely improved.

Biogeography and biodiversity questions: Large-scale studies focusing on species composition and richness have been limited on local communities (e.g., DUNN & al. 2009), higher taxonomic levels (e.g., genera in GUÉNARD & al. 2012) or restricted to regional distribution (e.g., northern Europe in BARONI URBANI & COLLINGWOOD 1977). The GABI database will offer the possibility to describe and study different regional, continental (e.g., WEPFER & al. 2016) or even global patterns of diversity. Those should be realized with the limitations of global incompleteness (see GUÉNARD & al. 2012) and potential misidentifications (see above). Within this context, GABI would provide a better understanding of the diversification patterns and evolutionary trajectory of different ant clades.

The future of GABI: challenges and possibilities

The effort invested in the GABI project should be continued to address missing information, improve the quality and accuracy of existing information, and keep up with future records. To this extent, the authors would like to invite ant biologists willing to share their data to contact the authors (BG). Scientists are particularly encouraged to verify if their relevant publications have been completely synthesized into our database. A complete list of references used for the development of GABI is available at the following address: <https://benoitguenard.wordpress.com/gabi-articles-full-list-2/> or on demand.

One of the main products of GABI is the production of distribution maps for all ant taxa, including 15,134 individual species and subspecies maps. Maps for the 333 valid and extent genera and for the 16 valid subfamilies have been produced based on the known distribution of nominal species; which does not include records from genera known only from morphospecies within a region; and their cumulative richness within each of the 592 regions defined here. All these maps are available on antmaps.org and are updated weekly directly from GABI, inheriting additions / modifications performed in the database.

A future major challenge as new and more accurate records become available is to increase the resolution at which each species distribution is presented. This, however, limits the scope of the type of data available for macroecological or biogeographic studies as many historical records unique to a region are only available for a very large scale (country). The latter might not be resolved (new species records in the same region) for years or even decades due to many areas that are undersampled and are not subject to ongoing inventory efforts (GUÉNARD & al. 2012).

While compiling data from two centuries of publications has constituted a major challenge, the future continuation of data recording is equally important. The manual extraction of published information is extremely time consuming and thus difficult to pursue in the academic world with limited funds. Scientists, interested in sharing their data can send us their new publication with their data directly formatted for GABI as presented in Table S1. In general, we would like to encourage scientists to fully publish their datasets within their publications or as an appendix, as promoted by several journals. This greatly improves the compilation of large databases, so that the entire scientific community can benefit by developing new tools such as GABI / antmaps.org, which ultimately help developing conservation plans to protect the species that are the core of our research.

A final challenge for keeping accurate distribution of each species is synchronizing data changes across databases (Tab. S2). Data revisions are performed continuously within different databases after the integration of these data into GABI. While most databases might possess accession numbers that can be used to synchronize records, complications arise when corrections or changes are made in one database within GABI. Other databases that might not have specific accession numbers could be even more problematic especially if the owner does not keep the history of the species identification status over time.

Conclusions

GABI represents one of the first comprehensive global databases of the species-level geographic distribution of any large group of insects. GABI should not be perceived as a final product but as a point of departure for myrmecologists. We hope that this new database will bring ants to where most groups of vertebrates stood about 15 years ago in terms of biodiversity informatics tools (DINIZ-FILHO & al. 2010) and will open a new era of research in macroecology, macroevolution, and conservation research on ants. With large areas of the world still unexplored or data largely incomplete (GUÉNARD & al. 2012) and important taxonomic work ahead for completing the inventory of ant species (WARD 2014), we hope that GABI will pro-

vide a new tool to ant biologists to facilitate their work and accelerate research progress. GABI and antmaps.org aim to build upon and complement other existing initiatives (e.g., AGOSTI & JOHNSON 2010, BOLTON 2014, ANTWEB 2015, ANTWIKI 2015, BOLTON 2015) that have provided tremendous benefits to myrmecology during the past decades. As with those efforts, the quality and utility of the GABI database as a resource will be greatly enhanced by the continued participation of the broader myrmecological community.

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