Insect conservation, technological traps, and the fading arts of natural history and field ecology

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Introduction

The union of modern technology and computational intelligence with conservation could be a Promethean gift to help humans avert impending catastrophes due to climate change, loss of biodiversity, and reductions in the density of key functional groups, including insect pollinators. As insect ecologists continue their struggle to document and protect global biodiversity (Slade and Ong 2023, Diamond et al. 2023, Leandro 2023), we seem to have a cornucopia of powerful methods, including artificial intelligence (AI) species identifications, access to big data, rapid advances in genomics, satellite data, and steadily improving drone technology, yet perhaps we are throwing out valuable tradition while rushing to embrace these tools. Wherefore and wither the naturalist (Futuyma 1998)? Indeed, what is the role of the naturalist or field ecologist in insect science today? As teachers and mentors, are we doing enough to maintain a focus on complex ecological interactions and natural history, especially in the tropics where there is so much work to do (Powers 2024)? Many ecologists are embracing large, synthetic databases and automated identification methods (van Klink et al. 2022), or even contests to remotely identify as many rainforest species as possible in 24 hours (https://www.xprize.org/prizes/rainforest) in areas where most insect species have not been described. At the same time, we may be forgetting the insight garnered by the slow contemplation of an entangled bank (Darwin 1859) or the awe-inspiring observations on a long Malay Archipelago voyage (Wallace 1869). The original methods of natural history and the joys of observing the natural world, collecting insects by hand, and using suites of morphological characters to assign a morphospecies categorization to an observed arthropod are central to taxonomic discovery and ecology. It is our contention that these practices need to remain at the center of any serious conservation effort to document and preserve biological diversity. What use is a list of species obtained by instruments on drones and identified to some taxonomic level with molecular barcodes or machine learning algorithms? Do we actually want a future in which a majority of diversity data are collected and curated with minimal human oversight? Now is the time to consider what would be gained and what would be lost in such a world. These concerns are especially relevant to understanding interaction diversity, which has been the focus of more attention as network science has been better integrated into ecology (Dyer et al. 2010). Here, we present current opinions on how to efficiently quantify biodiversity without abandoning careful natural history and ecology studies on the ground.

Recent reviews and editorials have summarized advances in technology that have putatively advanced or are on the verge of revolutionizing the study of insect biodiversity (e.g., van Klink et al. 2022, Powers 2024), highlighting new methods to collect, analyze, and interpret ecological data. A review by van Klink et al. (2022) focuses on computer vision, acoustic sensors, radar, and molecular methods, and these modern and not-so-modern methods are often touted as answers to the biodiversity crisis. With these new methods, subdisciplines such as barcoding taxonomy, conservation-omics, and even aeroecology are gaining traction as the focus for diversity research and funding (e.g., Gostel et al. 2022, De León et al. 2023). Combined with recent developments of more powerful drones, new methods do indeed have the potential to advance diversity surveys and inventories by improving speed and capacity (Madden et al. 2022). In fact, drones are an increasingly employed method in ecology used to capture high-resolution images and collect samples from hard-to-reach areas, potentially providing terabytes of data for insects in all terrestrial ecosystems. There is no doubt that these images have provided insights not possible without them. Furthermore, many of the newest tools are seen as almost a requirement for biodiversity research, including AI, environmental DNA (eDNA), DNA barcoding, and big data platforms. Statistical approaches that fall under the umbrella of machine learning are now widely used for analyzing images, identifying species, and automating the initial stages of biodiversity research. Although not novel for insect science, molecular methods, including the use of eDNA and DNA barcoding, are still rapidly evolving and have enhanced species detection and identification efforts considerably. Finally, big data facilitates inferences related to ecological interactions by integrating diverse sources of data, while AI-powered systems are used for classification and species identifications.

A defense of natural history and critique of selected modern methods

Traditional natural history

The observational methods employed by Pliny the Elder (*Naturalis Historia*, 79 CE) two thousand years ago, particularly for Hymenoptera and Lepidoptera, might appear inconsequential or naive when compared to the scientific tools available today. However, despite the promise of current approaches, traditional methods of studying biodiversity via focused observation, physical collection, and morphological descriptions remain foundational, providing important insights that continue to complement modern techniques. These pillars of insect science are part of basic natural history, and although they are time-intensive, they yield rich data about insect behavior, systematic relationships, and ecological roles. Direct observations of insects and their interactions within ecosystems offer nuanced understandings that technology alone cannot currently capture. In most cases, manually trapping or directly collecting insects should be the primary methods for biodiversity surveys and inventories that are needed for both research and conservation efforts. Morphological analysis remains important for species identification and the description of new species, despite being time-consuming and requiring specialized expertise. Although the issue is of course not unique to insect science, researchers face challenges with complex analyses and the task of understanding and synthesizing the scientific literature that continues to grow at an unmanageable rate. AI, which includes increasingly popular machine learning methods, has promised solutions to these challenges. While the benefits might be obvious, for example for rapid insect identification and the speed with which code can be written in popular statistical languages, the costs are not yet apparent and might be accruing, where depth of consideration is sacrificed for speed of publication (e.g., London, and Kimmelman 2020, Ioannidis 2005, Smaldino and McElreath 2016).

Barcoding

A transformative addition to the insect natural historian's toolbox is the increasing use of molecular methods that have rapidly advanced over the past 50 years, including DNA "barcoding." For insects, barcoding typically involves sequencing a short stretch of the mitochondrial gene for the enzyme Cytochrome Oxidase I (COI), which is then compared to available databases for the purpose of generating species lists for a sample or region, and for contributing to taxonomic revisions and species descriptions (Wilson 2012). However, the reliance on such barcodes has in many areas of study eclipsed traditional methods and surprisingly has also made it difficult to embrace more advanced genetic tools. For example, projects focused on rearing immature insects to get estimates of trophic interaction diversity employ inexpensive methods for estimating this dimension of biodiversity and yield museum specimens that can be used for phylogenomics or conservation research (e.g., reviewed by Salcido et al. 2022). Yet, some have argued forcefully that barcoding is needed for these projects for immediate identification of immature insects or their parasitoids and have even argued that barcoding makes the public more bio-literate (Janzen and Hallwachs 2021). Given the worsening taxonomic impediment (Meier et al. 2024) and the alarming rates of insect species losses, especially in the tropics (Wagner et al. 2021), it is not productive to insist that all studies in insect biodiversity and taxonomy should rely on this or any other one approach that is tied to a particular technology (e.g., Meier et al. 2024). Incomplete taxon sampling is also a serious problem with the barcoding approach to characterizing both communities and building phylogenies (Meyer & Paulay 2005; also see Virgilio et al. 2010), and this is especially relevant to the hyper-diverse insect taxa found in the tropics. It has not been difficult to find examples where the barcode fails to separate recognized taxa of Lepidoptera (Gompert et al. 2006, Forister et al. 2008, Wilson et al. 2012), and issues with barcoding have been widely discussed in the literature (e.g. Rubinoff et al. 2006, Taylor and Harris 2012, Mallo and Posada 2016). Finally, in the areas of the world where biodiversity research is needed the most – tropical rainforests – there is a dearth of sequence data in the BOLD database for most taxa of insects – in fact, BOLD covers about 4% of the conservative estimate of 5.5 million existing species of insects (van Klink et al. 2022). In these areas that are rich in undocumented biodiversity it makes more sense to prioritize collecting natural history data, getting collections into museums, and pairing molecular with morphological approaches for estimating species and interaction diversities.

Modern population genetics and phylogenetic analyses utilize high-throughput next-generation sequencing (NGS) often paired with reduced representation approaches such as double digest restriction-site (ddRADseq) or genotype-by-sequencing (GBS) to quickly generate information on thousands or tens of thousands of loci. Sequencing approaches are advancing rapidly, and whole genome sequences are now being generated in highly replicated population or systematic studies (Ribeiro and Espíndola 2023, Webster et al. 2023). GBS, for example, offers far greater resolution and scalability compared to traditional barcoding, making it a superior tool for fine-scale population studies and similar applications (Andrews et al. 2016). Seen in that light, the insistence on traditional barcoding does not necessarily offer much above and beyond traditional morphological approaches to species identifications and descriptions (e.g., Chapple & Ritchie 2013), and may in fact be a hindrance to biodiversity research in the extent to which a field becomes anchored to a single, ossified technology. We recognize of course that the picture might be different if an important fraction of insects had actually been "barcoded," but see the estimate of 4% above. Nevertheless, one often hears the informal argument that having molecular data is still better than morphology since it is at least possible to generate a phylogenetic hypothesis using COI data. Among other issues, this argument ignores the problem that the utility of one small fragment of DNA is expected to drop in proportion to the speed and breadth of adaptive radiations, which of course characterize much of insect diversity. This is because ancestral polymorphism is retained across species boundaries in rapidly radiating groups, which interacts with the problem of mitochondrial introgression through hybridization. In either case, for species lists and rapid interaction diversity assessments, a morphological focus still generates specimens that can be preserved in museums and later used in population genomic, phylogenomics, or genetic diversity studies. There is an appealing irony here that the older, museum-based approach is more flexible and facilitates evolving approaches and methodologies which we of course support, as long as the foundations of our field are not abandoned.

Satellite imagery and modern drone technology

Remote sensing technology includes satellite and airborne sensors, spanning a gradient in methodologies, including diverse types of satellite data, airborne drones, tractor drones, and ground lidar. These approaches offer powerful tools for estimating insect diversity or associated ecological variables, with satellite data providing the highest spatial and temporal resolutions. Enhancements in these technologies have yielded observations of insect habitats and behavior, detailed data on habitat structure, estimates of insect herbivory, measures of light pollution, long-term climate data, microhabitat weather parameters, and detection of insects (Rhodes et al. 2022). Guided by causal hypotheses about how these observed variables are related, these technologies will help us understand how global change parameters are affecting insect populations and diversity and could help with management or conservation decisions.

Similarly, drones are already enhancing insect diversity surveys by enabling the collection of more data from previously inaccessible or challenging environments, especially canopies and other upper layers of forests, which are often rich in insect diversity (de Souza Amorim et al. 2022) but difficult to reach. Drones can also be used to collect foliar canopy samples, spectral data (e.g., Raman spectroscopy, Sharma et al. 2023), and insects via drone-delivered insect traps (lost Filho et al. 2020). Specialized drone sensors provide a method to collect audio and video data, high resolution images, and eDNA from canopies, phytotelmata, and other hard to reach communities, allowing for indirect detection of diverse insect communities that are otherwise difficult to census. When combined with technological advances summarized here, drones have the potential to significantly enhance biodiversity surveys and inventories.

Clearly, advanced remote sensing technologies delivered via drones and satellite data offer significant advantages for insect diversity surveys and assessments, but traditional trapping and observational methods offer rich information that these technologies alone cannot provide (e.g., de Souza Amorim et al. 2022). Malaise, light, pitfall, and other trapping methods combined with physical collecting and searching allow for the direct observation of seasonal changes and species behaviors, vertical canopy stratification, life history traits, and interactions with other species, all of which are components of functional and interaction diversities – which likely provide more insight into stability and ecosystem function (Dyer et al. 2018). And, in an increasingly urbanized world, the urban bioark is best sampled using these traditional methods (Diamond et al. 2023). Furthermore, questions about insect persistence in the face of global change need to utilize traditional approaches like systematics, assessments of species abundance, and insect disease ecology (Mason and Shikano 2023), all of which require physical sampling for morphological and genetic analyses that remote sensing alone cannot achieve.

Big data

Large, aggregated databases from noninteractive citizen science projects (e.g., Prudic et al. 2023, Plummer et al. 2024), data repositories like the Encyclopedia of Life (EOL), and pooled data from labs worldwide (Forister et al. 2015) represent a unique feature of modern ecology, in which anyone with a smart phone and no training can contribute potentially valuable data through free platforms like iNaturalist. However, there are shortcomings and challenges, even if the methods are relatively standardized (Robinson et al. 2023). The main issues with these approaches are: 1) the lack of direct observations for many aggregated databases; 2) unstandardized methodologies including, in many cases, a lack of absence-data or negative observations; 3) poor or variable quality control; and 4) less time in nature for individual investigators. Direct observations by researchers working with organisms in the field remain the gold standard for understanding ecological interactions (Powers 2024, Dyer et al. 2010), including insect-plant, insect-predator, and insect-soil interactions, and without such natural history, we are more likely to get inaccurate assessments of insect roles and interactions within a focal ecosystem (Dickinson et al. 2010). Lack of standardization for data collected by different citizen scientists or research groups used to create big data can reduce data reliability for meaningful inferences (Bird et al. 2014). Lack of quality control is perhaps less important for combined citizen science datasets that follow a specific method, but many big datasets combined from diverse sources may not include sufficient validations or verification processes, undermining their utility (Kosmala et al., 2016, but see Dyer et al. 2016).

Another manifestation of big data involves the aggregation of -omics databases. In contrast to databases generated from dispersed or publicly-sourced observations, the -omics perspective involves the combination of many different types of data, often sourced from different labs with different technologies. For example, this could involve the combination of genomics with metabolomics, proteomics, and even phenomics as the compilation of phenotypic (including morphological) data (Houle et al. 2010). On the one hand, it is impossible to dispute the value to organismal biology that potentially derives from datasets that link such disparate types of information. On the other hand, the value of such aggregation can only be as good as the information that binds different datasets together, which of course brings us back to the need for the most rigorous taxonomic information, which should not be based solely on COI barcoding. Moreover, -omics approaches in ecology and evolutionary biology will often happen at the scale of species, which presents a number of challenges in light of all the issues discussed above. For example, automated AI-based identification will often produce identifications above the species level (e.g., to taxonomic order), which limits the extent to which they can be merged with -omics datasets. Even when species-level identifications are possible, we should be cautious of the extent to which relevant mechanisms can be understood at that level. A contemporary example is the goal of assembling global or regional trait databases for insects which can, in theory, be merged with monitoring databases to investigate relationships between population trajectories (or responses to climate) and ecological traits. We have ourselves contributed to such analyses, but we also acknowledge that variation below the species level is almost certainly required to achieve a meaningful understanding of population biology and adaptation.

But the most important argument that should temper our enthusiasm for science based only on big, aggregated or -omics datasets is that they yield less time in nature for the authors of papers using these data. Direct engagement with the natural environment is essential for developing a deep understanding of insect ecology (Powers 2024, Bonney et al., 2014) and for advancing theory, and it is not hard to find examples in which conceptual advances stagnate without fresh insights from the field. For example, the match-mismatch hypothesis was an early expectation from the area of global change biology that warming temperatures would lead to a mismatch in the phenology of consumers and resources. While this might be true for extremely specialized and obligate interactions, many field biologists would expect spatial dynamics to dilute mismatch effects since most consumers already deal with temporal heterogeneity in the availability of resources across the landscape. And, indeed, based on meta-analysis of careful studies, evidence for the match-mismatch hypothesis is weak (Kharouba and Wolkovich 2023). In other cases, predictions based on theory might be borne out by work with large, aggregated datasets, but explanations cannot be generated without work in the field. For example, another early expectation from global change biology is the idea that geographic ranges will shift with warming temperatures as organisms move to track climatic niches along latitudinal and elevational gradients. Those patterns can indeed be detected based on large-scale datasets, but there is also consensus that direct observations and experiments with wild organisms are essential to understanding mechanisms (see Hsiung et al. 2018 for a discussion in the context of elevational movement). All of this reinforces the value of field experiences and observations, which are not simply complementary to other approaches, but will remain the fount of both the highest quality data and insights leading to new theory.

Conclusion

AI, drones, DNA barcoding, -omics, remotely collected big citizen science databases, and development of rapid diversity assessments are certainly helping efforts to characterize the insect communities found in the most diverse ecosystems such as lowland tropical wet forests. However, technology and methods evolve rapidly, so there should be flexibility that prevents a single methodological approach, such as barcoding, from becoming entrenched. In contrast, the relatively unmodified observational methods of traditional naturalists and field ecologists are still the most important part of modern biodiversity studies. Even when they are overshadowed by the glitter of new approaches, it is our contention that insect biology and biodiversity studies still rely fundamentally on field- and organismal-based knowledge. When combined with less technologically alluring methods or ways of knowing that are centered on traditional natural history, insect ecologists will make substantial progress towards characterizing diversity, setting conservation priorities, and protecting insects (Leandro 2023). These methods can be improved, but not replaced, by modern technologies. Declines in insect diversity will continue despite our best efforts, and they are yet another emerging feature of global change. Battling these declines, mitigating their impacts, and attempting to document multiple dimensions of insect diversity as these dimensions are rapidly degrading will all require multiple concerted approaches (Forister et al. 2024). Certainly, the methods we critique here will be a key part of these battles, but not at the expense of basic natural history.

Finally, we ask that we, as a field, seriously consider our long-term goals and always ask if particular technological advances impede or enable progress. As a thought experiment, imagine a world in which remaining natural areas are outfitted with a high density of remotely-operated visual, chemosensory and auditory detectors that report on the identity and presence of all insects that pass near the sensors. This kind of monitoring will by definition focus on adults, which are not always the life history stage with the greatest ecological impact, but we can ignore that for the moment. There is also a massive issue of electronic waste that should be considered, especially when the recycling of such waste is a burden that wealthy countries typically put on the most vulnerable individuals in less developed nations. But, let us assume for the moment that the waste issue can be meaningfully addressed; and let us also assume that the sensors can themselves be made inconspicuous. Then one could argue that the impact on natural ecosystems would only be positive, as it would provide researchers and the public with real-time feedback on, for example, climate change impacts on wild populations. Or, one can ask if anyone in that future would still care about insects. Human beings have a well-recognized issue with entomophobia that can get worse as people reduce their exposure to the natural world (Gardiner and Roy 2022; Soga and Gaston 2022). Thus an army of drones might inventory a rainforest, or at least generate some kind of tentative catalog (albeit without data on ecological interactions), but does that inventory increase our political or societal motivation to protect the forest? If the answer is no, then we should not fool ourselves that technological advances will solve the human problem that is of course at the root of the biodiversity crisis. In any and all cases, we know that vast hosts of species will be gone before they are known to modern science. It is our contention that knowing fewer of them, by direct observations and with well-curated specimens, will be preferable to knowing more of them with less comprehensive information about each.

In summary, we of course know that insect biology and ecology must take advantage of novel technologies and approaches, some of which are summarized in the other articles collected in this issue. It has not been our goal to belittle the potential value of the newest approaches, rather we want to encourage researchers to critically evaluate all technologies and not assume that new is better especially when so much is at stake.

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