The Value of Citizen Science in Increasing Our Knowledge of Under-Sampled Biodiversity: An Overview of Public Documentation of Auchenorrhyncha and the Hoppers of North Carolina

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Due to the increasing popularity of websites specializing in nature documentation, there has been a surge in the number of people enthusiastic about observing and documenting nature over the past 2 decades. These citizen scientists are recording biodiversity on unprecedented temporal and spatial scales, rendering data of tremendous value to the scientific community. In this study, we investigate the role of citizen science in increasing knowledge of global biodiversity through the examination of notable contributions to the understanding of the insect suborder Auchenorrhyncha, also known as true hoppers, in North America. We have compiled a comprehensive summary of citizen science contributions—published and unpublished—to the understanding of hopper diversity, finding over fifty previously unpublished country and state records as well as dozens of undescribed and potentially undescribed species. We compare citizen science contributions to those published in the literature as well as specimen records in collections in the United States and Canada, illuminating the fact that the copious data afforded by citizen science contributions are underutilized. We also introduce the website Hoppers of North Carolina, a revolutionary new benchmark for tracking hopper diversity, disseminating knowledge from the literature, and incorporating citizen science. Finally, we provide a series of recommendations for both the entomological community and citizen science platforms on how best to approach, utilize, and increase the quality of sightings from the general public.

Keywords: environmental education, community research, BugGuide, iNaturalist, leafhopper, treehoppers, planthopper, spittlebug

INTRODUCTION

In the last 2 decades, a number of citizen science platforms have been developed, leading to an explosion in the amount of people enthusiastic about observing and documenting nature (Hand, 2010; Bonney et al., 2014; Cox et al., 2015; Cooper, 2016; Aristeidou et al., 2021). These citizen scientists are collectively and opportunistically recording biodiversity on unprecedented temporal and spatial scales (Boersch-Supan et al., 2019; Fink et al., 2020). Citizen science data has therefore been receiving
heightened attention from the scientific community in recent years (Adler et al., 2020). One well-known example of citizen science is eBird, a community science database that enables birdwatchers from around the world to contribute observations of birds (Sullivan et al., 2009; Amano et al., 2016). This enormous, long-term, and continuously growing dataset of bird count data consists of nearly a billion observations (Neate-Clegg et al., 2020) and can allow scientists to perform robust studies such as assessing avian population trends (Clark, 2017; Walker and Taylor, 2017; Horns et al., 2018; Fink et al., 2020), monitoring bird migration (Fournier et al., 2017; Horton et al., 2018), and helping inform the conservation of threatened species (Sullivan et al., 2017; Robinson et al., 2018; Lees et al., 2021). Similar bird observation data has also been used to model the effects of climate change on future distributions of bird species (Abolafya et al., 2013). However, there is a big difference between documenting birds and harder to identify taxa such as arthropods; not only are birds fairly well-known and more charismatic to the general public in comparison to most arthropods, but birds are typically much less challenging to photograph and identify, therefore being fairly easy to document (by both sight and sound). Furthermore, research has shown that while documentation of birds by the public has significantly increased in recent years around the world, data accumulation for non-avian taxa has not similarly accelerated (Amano et al., 2016).

One taxonomic group that has benefited from citizen science contributions is Auchenorrhyncha, an incredibly diverse group of herbivorous insects commonly referred to as true hoppers (hereafter referred to as “hoppers”). In North America, these hoppers consist of spittlebugs (Aphrophoridae, Cercopidae and Clastopteridae), leafhoppers (Cicadellidae), treehoppers (Membracidae and Aetalionidae), and planthoppers (Fulgoroidea). Cicadas (Cicadidae)—excluded from this study—also belong to Auchenorrhyncha and, while not every cicada genus is easy to identify, this group tends to receive heightened attention and recognition due to their life cycles, size, and audible courtship calls (Deitz, 2008). In contrast, the remainder of hoppers on the other hand (being mostly small and skittish) tend to go unnoticed in the public eye, with only the most economically significant species receiving attention. As a result, there is a significant lack of information for most hopper species including biogeography, host history, and disease vector status. To further complicate matters, hopper taxonomy can often be extremely complicated and fluid, with some genera going decades without much-needed revision and the validity of certain species in doubt. There are also various schools of thought towards hopper taxonomy which often leads to conflicting methods of classification (Takiya, 2007).

The number of hopper taxonomists in the United States and Canada has been steadily rising after a steep decline in the late 1980s (though the overall number of hopper specialists is still low), with emerging tools and academic programs having enabled a resurgence in the number of entomologists proficient in hopper studies within the past 2 decades (Dietrich, 2013). An often overlooked “tool” that has continually increased the understanding of hoppers is citizen science. With constant monitoring of global biodiversity by hundreds of thousands to millions of people (Bonney et al., 2014; Jarvis et al., 2015), an unprecedented amount of data is now readily accessible to researchers. While most museum collections worldwide have not yet been digitized, citizen science data is instantly available and denotes a new era of scientific accessibility.

In this study, we examine the value of citizen science websites and citizen scientists in helping increase our knowledge of understudied and under-sampled taxonomic groups, specifically focusing on Auchenorrhynchan hoppers. We provide an overview of the contributions of records on the citizen science websites BugGuide and iNaturalist in furthering our understanding of the abundance and distribution of various hopper species and compare this data with collection and specimen records. We highlight previously published examples of how citizen science can lead to the identification of new state and country records, the monitoring of introduced species, and even the description of new taxa. Additionally, we introduce the Hoppers of North Carolina website (hereafter shortened to Hopper Site: https://auth1.dpr.ncparks.gov/bugs/index.php) as a case study for the scientific community. This site is an updated approach to citizen science and knowledge dissemination, combining various online contributions with the scientific approach (characteristic of the entomological field) in studying arthropod biodiversity. Finally, we suggest how we, as scientists, can interact with and train the younger generations of amateur naturalists in order to maximize the value and accuracy of citizen science-based information.

METHODS

Literature Review
In order to evaluate the contributions of citizen science to the published study of Auchenorrhyncha, we conducted a systematic search of peer-reviewed literature on hoppers published since 2004, the first year after BugGuide was officially launched (BugGuide, 2021), in both Web of Science and Google Scholar. We narrowed our search to North America (United States and Canada) and used search terms—separated by commas—related to citizen science, the four main taxonomic groups of hoppers, invasive species monitoring, and the description of new species (Supplementary Table S1). We then narrowed our focus to publications that noted new state or country records of described species or the description of new taxa that were discovered thanks to citizen science documentation.

BugGuide and iNaturalist
Citizen Science Background
BugGuide.net and iNaturalist.org are two popular websites for recording and hosting nature observations, especially in the United States. These sites are generally focused on public outreach and biological education, but they also have much to offer scientifically. The inexperienced observers, the most dedicated enthusiasts, and experts leading their respective fields all merge in the communities that these sites build. The two sites strongly utilize the work of volunteers and are both substantial achievements in the realm of citizen science, although there are key differences between them.
BugGuide is an interactive online field guide that focuses on arthropods north of Mexico. Users are required to upload a photograph, a date, and a location for each entry. A user may move their own entry throughout the taxonomic tree of the site, but only designated Contributing Editors and a select few other roles may move images uploaded to the site within the Guide, add taxa to the site, and make edits to the site taxa. Entries that are deemed of little use to the Guide are deleted after a notification in 30 days. This high level of curation allows the site to be more selective in its presentation and favor a high standard of data quality, but also limits user interaction, as only selected curators can make changes on the site. Contributing Editors may also edit “Info” pages, which enable users to view a curated informational wiki that presents information on identification, taxonomic history, host preferences, distribution, and the number of child taxa (more specific taxonomic units, i.e. the number of genera in a tribe or the number of species within a genus).

This is in contrast to the globally-oriented iNaturalist, which is an online social network and identification system for amateur naturalists that was established in 2008 (Seltzer, 2019). iNaturalist does not take the same field guide approach as BugGuide and instead is mainly based around the users, with minimal hierarchy beyond simple site moderation and taxonomic curation. The site globally covers all biota, as opposed to BugGuide’s focus on North American arthropods. When a user uploads an observation, an AI (artificial intelligence) will suggest a possible identification. Once the observation is uploaded, any user may suggest a taxon identification which informs the “Community ID,” a voting-based identification system where each vote holds equal weight (regardless of a user’s administrative role). The authoritative editors on iNaturalist are Curators and Staff, who moderate the taxonomic and social sides of the site. Selecting a taxon in iNaturalist immediately presents users with a view of user-based statistics, as well as three graphs illustrating the seasonality, history, and observed life stages of observations of the taxon. There is also an interactive distributional map for the taxon, showing coordinate-based pinpoints for each observation. These distributional maps are based on Google Maps and are much more advanced and precise than the BugGuide distributional maps, which simply note which states or provinces a taxon occurs in.

**Data and Statistics**

Data from BugGuide were obtained (on May 11, 2021) through the (as of writing) beta website BugGuide 2.0, which allows users to see the number of observations within a taxon when the “Info” tab is selected. The number of entries for Auchenorrhyncha was recorded with the number of Cicadoidea observations subtracted.

Data and statistics from iNaturalist were obtained (on May 11, 2021) by searching “Auchenorrhyncha” through the “Explore” page (also referred to as “Observation search”). The location field was left blank to obtain global results. Data for Cicadoidea were excluded through the use of an extension added to the end of the URL which excludes a specific taxon from the search: `http://www.inaturalist.org/observations?&without_taxon_id = (taxon_id)`. The numbers of observations, species, identifiers, and observers were recorded based on the results of the search. Then, iNaturalist data for observations in North America were obtained through the creation of a “Collection Project,” which enables users to set certain parameters for a more specific search, including the addition and/or exclusion of multiple locations and taxa. Cicadoidea was again excluded from the search and the geographic range of the Collection Project was confined to the United States and Canada, excluding Hawaii and island territories.

Observation data on iNaturalist is divided among three categories: “Casual,” “Needs ID,” and “Research Grade.” “Casual” observations are entries that lack associated images, dates, and/or locations—we have excluded such observations from all searches made for this study. “Needs ID” observations are entries that include all of the aforementioned metadata that a “Casual” observation would lack, but have only been identified to a taxon higher than species-level or have been identified to species by only one user. “Research Grade” observations are entries that include all required metadata and have been identified to species by two or more users without a dissenting identification or have a majority of identifications in agreement. For the purposes of this study, we used both “Research Grade” and “Needs ID” observations.

To compare citizen science records on BugGuide and iNaturalist with those in collections, we searched records for spittlebugs (Aphrophoridae, Cercopidae, Clastoptera), leafhoppers (Cicadellidae), treehoppers (Membracidae, Aetalion), and planthoppers (Acanaloniidae, Achilidae, Caliscelidae, Cixiidae, Delphacidae, Derbididae, Dictyopharidae, Flatidae, Fulgoridae, Issidae, Kinnaridae, Nogodinidae, Tropiduchidae) for the continental United States and Canada on the “Search Records” page of iDigBio.org, an online database of digitized collection-based specimen data (iDigBio, 2021). While iDigBio does not necessarily contain data from every collection in North America, it has fantastic reach and functions as the coordinating center for the national effort by collections to digitize their specimens (iDigBio, 2021), therefore serving as a great representation of collections across the region. We then summed these records to produce an overall number of collection records for hoppers in North America.

We also compiled a list of country records as well as state, provincial, or territory records of recently described hoppers in North America that were submitted by citizen scientists to either BugGuide or iNaturalist and have not yet appeared in the literature. Additionally, we compiled a list of known undescribed and potentially undescribed (consisting of “probably” and “possibly” undescribed taxa) hopper species that have been documented on these citizen science platforms. For this paper, a “known undescribed” hopper is one that has been confirmed by experts, either via specimen analysis, dissection, or genetic barcoding, to be an undescribed species that has yet to be formally described. A “probably undescribed” hopper is one that is most likely undescribed but we are unaware of there being any proper specimen analysis by an expert to confirm this. A “possibly undescribed” hopper is one that does not currently seem to match anything in the literature but we cannot completely rule out a poorly known species or an unknown color form of something described. For both lists, we noted which state or province these hoppers have been recorded in, the online source of the records, and the initial identifier of these records. We also noted which record entries have been confirmed via specimen analysis.
Hoppers of North Carolina Website Background

In North Carolina, there is a significant focus on researching and documenting wildlife, particularly arthropods. The state has many resident entomologists, experienced field naturalists, and experts from both within and outside the state conducting research (NCBP, 2017). As a result, there is a great deal of information about arthropod taxa in the state and a growing focus on making this information available to the public online. A *Butterflies of North Carolina* website was created in 1994 (LeGrand and Howard, 2021), and then *Dragonflies and Damselflies of North Carolina* went online in 2010 (LeGrand et al., 2021). These original two online taxonomic databases for North Carolina disseminate knowledge of species distributions, natural and life history, identification, and conservation status to the public, serving as the authoritative sources for these two taxonomic groups in the state. These sites are open to the public, allowing any person to find a comprehensive list of the butterflies and odonates known to occur in each county, learn how to identify these species, and peruse a library of images taken in the state for each species. In the case of *Dragonflies and Damselflies of North Carolina*, the public can submit their own records and photographs directly to the database.

With this hybrid perspective in mind, the first author began in summer 2013 to develop a website to increase the overall knowledge of the spittlebugs, leafhoppers, treehoppers, and planthoppers found in North Carolina. The *Hopper Site* was developed through a partnership with the North Carolina State Parks System (Kittelberger and Howard, 2021). In May of 2017, the overall development of the *Hopper Site* was completed and the site was opened up to public use and record entry. The *Hopper Site* has three main functions: an online photographic field guide, records database, and citizen science platform (Kittelberger and Howard, 2021).

The *Hopper Site* is also a part of the North Carolina Biodiversity Project (NCBP), a private organization whose mission is to promote public interest in the state’s native species and ecosystems and their conservation (NCBP, 2017). This organization, which works in partnership with the North Carolina Division of Parks and Recreation, is composed of taxonomic experts, conservation biologists, science educators, and others that have had a long history of studying particular taxonomic groups in North Carolina. The NCBP currently consists of twenty websites and checklists for various taxa and serves as the most complete online coverage of the biodiversity in North Carolina.

### Data and Statistics

Information on the usage of the *Hopper Site* was obtained by the site administrator entering the records into a database table. All the records were then extracted into a CSV file, and the number of both contributors and different “observation types” were tabulated using back-end administrative tools accessible to the site administrator.

### RESULTS

#### Value of Citizen Science in the Knowledge of Hoppers Based on Literature Review

In our search of the literature, we found 10 publications that listed noteworthy records of 17 species that are specified as being either documented by individual citizen scientists (1 species; McKamey and Sullivan-Beckers, 2019) or contributions made to online citizen science platforms in North America (BugGuide or *Hopper Site*) Table 1. We also located one publication (Leavengood et al., 2017) containing a noteworthy record that was found by a member of the public but

| Scientific name | Record type | Literature source | Citizen science site(s) noted |
|-----------------|-------------|-------------------|-----------------------------|
| Leproyria angulifera Uhler, 1876 | State record (GA, NC, NY, MI, VT) | Hamilton, 2012 | BugGuide |
| Clastoptera oconotata Hamilton, 2015 | New species (SC, NC) | Hamilton, 2015 | BugGuide |
| Balclutha rubrostriata Melichar, 1903 | Country record (USA)NT | Zahniser et al., 2010; Carlson et al., 2012 BugGuide |
| Erasmoneura atra Johnson, 1935 | State record (NH) | Chandler and Hamilton, 2017 BugGuide |
| Eupteryx aptocynta Goeze, 1778 | State record (NH)NT | Chandler and Hamilton, 2017 BugGuide |
| Eupteryx decemnotata Rey, 1891 | State records (NC, NJ, NM, UT)NT | Clifré and Barringer, 2017; Tasi and Lucky, 2020 BugGuide, Hoppers of NC |
| Empoasca kittebergeri* Chandler and Hamilton, 2017 | New species (NH) | Chandler and Hamilton, 2017 BugGuide |
| Empoasca murray* Chandler and Hamilton, 2017 | New species (MA, NH) | Chandler and Hamilton, 2017 BugGuide |
| Hebata zancus Hamilton and Langor, 1987 | State record (VT) | Chandler and Hamilton, 2017 BugGuide |
| Hishimonus setulus Uhler, 1896 | Country record (USA)NT | Hamilton, 2011 BugGuide |
| Issyus linaeus Linnaeus, 1761 | Country record (CAN)NT | Hamilton; 2011; Carlson et al., 2012 BugGuide |
| Tremulicerus fulgidas Fabricius, 1775 | Country record (USA)NT | Carlson et al., 2012 BugGuide |
| Clastoptera octonotata | Country record (CAN)NT | Hamilton, 2011 BugGuide |
| Lepyronia angulifera | Country record (USA)NT | Hamilton, 2011 BugGuide |
| Kittelberger et al. Citizen Science and Hemipteran Hoppers | New species (KY) | McKamey and Sullivan-Beckers, 2019 BugGuide |
| Asaropus palmarum Horvath 1921 | State record (TX)NT | Leavengood et al., 2017b BugGuide |
| Haplaxius ovatus | State record (FL) | Wheeler and Wilson, 2014 BugGuide |

*These species are currently unplaced within the tribe Empoascini, as they were not treated in the latest revision of the tribe (Xu et al., 2021), which redefined its component genera.

This publication was not found in our initial search of the literature, since it does not include any reference to citizen science, and instead was found when we were looking for information on the year this species was introduced in California.

State abbreviations: FL = Florida, GA = Georgia, KY = Kentucky, MA = Massachusetts, MI = Michigan, NH = New Hampshire, NJ = New Jersey, NM = New Mexico, NY = New York, NC = North Carolina, SC = South Carolina, TX = Texas, UT = Utah, VT = Vermont.

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**TABLE 1** | Noteworthy records of hopper species in North America that were mentioned in the literature as being documented by citizen scientists, either individually or on a citizen science website. U.S.A = United States of America, CAN = Canada; abbreviations are used for states. INT indicates an introduced/adventive species.
which does not list the citizen science platform (BugGuide) to which this record was initially submitted (see Table 1 for more details). Of these 18 species, seven appear to represent first country records and seven represent first state records, while four are recently described species (Table 1; Chandler and Hamilton, 2017; Hamilton, 2015; McKamey and Sullivan-Beckers, 2019), demonstrating the value of citizen science in helping detect the presence of undescribed species.

There is great potential for citizen science to function in a passive surveillance role of hoppers, with the identification by experts of individual arthropods that were photographed by someone else. This passive surveillance can be especially instrumental in helping detect recently introduced species in North America (Hamilton, 2011; Carlson et al., 2012). Several nonindigenous insects were first detected in the United States and/or Canada via submissions to BugGuide (Hamilton, 2011; Carlson et al., 2012), including seven hopper species (Table 1; Carlson et al., 2012; Hamilton, 2011; Zahniser et al., 2010). Likewise, passive surveillance by citizen scientists can help experts document and monitor the spread of these introduced and, in some cases, invasive species (Table 1; Chandler et al., 2012; Hamilton and Sullivan-Beckers, 2017; Ciafré and Barringer, 2017; Leavengood et al., 2017; Tasi and Lucky, 2020). On the other hand, misidentified species that would represent first records for North America can make their way into the literature (see Protebrulla tertia in Carlson et al., 2012). This misidentification of notable records could be problematic for what would be any introduced and potential pest species, underscoring the need for a high standard of vetting of species identifications on citizen science platforms.

Citizen science can also provide insight into adult-nymph associations, interspecies relationships, population growth and decline, host plant data, and previously undocumented or poorly known behaviors of hoppers (Hamilton, 2011). It has even been cited as helping shed light on potential taxonomic relationships between treehoppers and leafhoppers, with photographic contributions of nymphs of both taxa on BugGuide providing supportive evidence that treehoppers may be neotenous leafhoppers (Hamilton, 2012). With the explosion of digital photography helping increase the documentation of all aspects of the life stage of hoppers in high detail in a way that might not have been previously available in collection-based specimens (Hamilton, 2011), citizen science can therefore play a role in furthering our understanding of the evolutionary history and systematics of these bugs (Hamilton, 2011, 2012).

We were unable to find any hopper literature in our search that referenced citizen science contributions from iNaturalist from North America. Even though there are far more Auchenorrhyncha hopper sightings and contributors on iNaturalist compared to BugGuide (see Results, BugGuide and iNaturalist), this absence of iNaturalist from the literature is likely a result of the site being several years younger than BugGuide and only having shifted to its current platform layout within the last decade. Additionally, in contrast with BugGuide, iNaturalist tends to be less taxonomically focused, have significantly more uploads, and any user can provide an identification of equal weight to an expert. Because of this, the veracity of sightings—particularly of lesser-known taxa—can sometimes be weaker than that of BugGuide. Perhaps these characteristics have prevented contributions from citizen scientists on iNaturalist from being valued as much as those on BugGuide by North American Auchenorrhyncha taxonomists. The small number of references to citizen science sites in hopper publications may also be a result of the small number of Auchenorrhyncha taxonomists in the United States and Canada. With only a dozen or so leading hopper taxonomists in North America, many focusing on global taxonomic groups and the training of new entomologists, publications citing citizen science contributions may be sidelined.

**BugGuide and iNaturalist**

As of May 10, 2021, there have been 59,907 hopper records uploaded to BugGuide (Figure 1). In comparison, as of May 11, 2021, there have been 310,740 hopper observations (of 4,360 identified species) uploaded to iNaturalist by 53,635 users. 167,157 of those observations were located in North America (Figure 1), with 1,343 different species recorded. Globally, 10,043 users contributed identifications. Therefore, there are 227,064 records for hoppers from iNaturalist and BugGuide in continental North America. In comparison (Supplementary Figure S1), on iDigBio we found 23,499 collection records of spittlebugs, 212,098 of leafhoppers, 79,734 of treehoppers, and 78,176 of planthoppers, resulting in a total of 393,507 hopper specimens in collections across continental North America (Figure 1). As a result, citizen scientists on BugGuide and iNaturalist have documented in less than 2 decades a number of individual hoppers that is equivalent to approximately 58% of collection records, largely from the 20th century, in continental North America. Additionally, on iNaturalist there has been a clear annual exponential growth between 2009 and 2020 in not only the number of observations of hoppers in North America but also the number of contributors (Figure 2), with 16,131 contributors submitting 78,923 observations in 2020.

We found records of 24 taxa that represent noteworthy records of hoppers documented first by citizen scientists online that have not yet been published in the literature (Table 2). There are 20 taxa that are apparent first country records for either the United States or Canada, with the other four taxa consisting of notable state records, including of two recently described species (Clastoptera octomotata Hamilton, 2015; Telamona stephani Wallace, 2018; Figures 3A,B). Seven of these taxa are also introduced species that are very recent additions to the North American fauna within the last couple decades (Acericerus ribaeti, Curtara insularis, Eupteryx decemnotata, Eupteryx fexicum, Tautoneura cf. polymitusa, Chloriona sicula (Figure 3F). Issus coleoptratus, Table 2). We also found five undescribed, four probably undescribed, and seven possibly undescribed taxa that have been documented by citizen scientists (Supplementary Table S2).

**Hoppers of North Carolina Description**

**Online Photographic Field Guide**

First and foremost, the Hopper Site functions as an online photographic field guide. The most notable feature of the site is its family photo gallery, an innovative approach to hopper identification that is designed to serve as a photographic key to species’ identification—it is both informative and easy to navigate. The page has a list of all the families representing the hopper fauna found in North Carolina, with subfamilies used to help organize and divide the speciose and diverse Cicadellidae (leafhoppers). Four photographs represent each family or subfamily on this page, allowing for comparisons of these groups and serving as the first step for aiding any user of the site that is trying to narrow down the identification of a hopper.
Clicking on the family or subfamily link above a set of four photos leads to a new page that displays images for all the species in that particular taxonomic group. There are typically two to three images representing a species, depicting, when possible, images of both adult sexes and the nymphal life stage. This gallery view allows a user to quickly and easily compare images of species, particularly those that are similar and challenging to distinguish. Clicking on the scientific name of a hopper then redirects a user to the profile page for that species.

The profile page for a species mirrors that of a species’ entry in a field guide and consists of six parts. At the top of the page are up to four diagnostic photos which, if important for a species’ identification, can include views of the male subgenital plates or female pregenital sternite. As on the family photo gallery pages, the adult male and female as well as the nymph are pictured, if possible. Below the photos is a “Taxonomy” section, which can include the family, subfamily, tribe, and in some instances subgenus the species belongs to, as well as listing the taxonomic author that described the species. Following this is an “Identification” section, consisting

![FIGURE 1](image1.png) **FIGURE 1** The number of hopper records through May 11, 2021 from North America (United States and Canada) in BugGuide, iNaturalist, and digitized collections in iDigBio. There are 59,907 BugGuide records and 167,157 sightings from iNaturalist. In comparison, there are 393,507 specimens in digitized collections in iDigBio.

![FIGURE 2](image2.png) **FIGURE 2** Growth on iNaturalist in the number of hopper observations (blue) and the number of citizen science contributors (orange) in North America (continental United States and Canada) from 2009 through 2020.
of a detailed description of how to identify the species, including when possible for both sexes and the nymph. Descriptions of the subgenital plates and pregenital sternite, morphometric information, and/or field marks distinguishing different subspecies are also included.

Next, there is a “Distribution in North Carolina” section that includes a state map, populated from county records with colors distinguishing the type of record (i.e., photographic record, visual sighting, external citizen science website source, or collection source). Clicking on a county will open a new tab with a list of each record for that county. Information about distribution, abundance, and seasonal occurrence follows the map, with seasonal occurrence also populated from submitted records. The fifth section is “Habitats and Life History,” which describes which habitats the species can be found in, what plant species it is associated with, and any interesting behavior. The status of the species in the state (native or introduced) is also noted, and a comments section is included which is often used by the author to provide helpful information such as how to distinguish the hopper from similar species and clarifying any taxonomic issues that may confound identification. Finally, there is a “Species Photo Gallery” which includes every photo submitted to the site for that species. Links are sometimes scattered across the profile page leading the user to other sites with additional photographs of live or pinned specimens, taxonomic accounts, or publications that were consulted to write the profile.

### TABLE 2 | Known country records and notable state records (either recently described or adventive species) of Auchenorrhynchan hopper taxa in North America that were first documented by citizen scientists but have not yet been mentioned in the literature. USA = United States of America, CAN = Canada; abbreviations are used for states and provinces. INT indicates an introduced/adventive species, and an asterisk * indicates a record that was confirmed via specimen, "cf" is used to indicate a taxon that most resembles an already described species, but identification cannot be confirmed without a specimen. The initial identifier column lists the original expert source(s) that provided identification of the first record(s) of a particular taxon; the list of names for these abbreviated names can be found at the end of the table.

| Scientific name | Record type | State or province | Citizen science source | Initial identifier |
|-----------------|-------------|-------------------|------------------------|-------------------|
| Aeneolamia abrolissioides Lallemant, 1939 | Country record (USA) | AZ | BugGuide* | VT |
| Aeneolamia contigua Walker, 1851 | Country record (USA) | TX | BugGuide* | VT |
| Cephaloptera brevipennis | Country record (USA) | TX | BugGuide | VT |
| Clastoptera octonotata Hamilton, 2015 | State records, new species | FL, AL, LA, TX | BugGuide | KK |
| Acericerus ribauti Nickel and Remane, 2002  | Country record (USA)* | NY, CT | BugGuide* | JK |
| Alygus mixtus Fabricius, 1794 | Country record (CAN)* | ON | Naturalist | SH |
| Curtula insularis Caldwell, 1952 | State records* | OK, TX, LA, MS, AL, GA, NC, SC | BugGuide, Hoppers of NC, | J, SH, KK |
| Dikrella scinitata Chandler and Hamilton, 2017 | Country Record (CAN) | ON | Naturalist | SH |
| Draeculeacphila inscripta Van Duzee, 1915 | Country Record (CAN) | ON | Naturalist | KK |
| Egidemia cf. inflata | Country record (USA) | TX | Naturalist | SH |
| Eupteryx decemnotata Rey, 1891 | Country record (USA)*, state records* | BC: AL, GA, MA, MD, MO, OR, TX, VA, WA | BugGuide, iNaturalist | KK, SH |
| Eupteryx iliccum* Newman, 1853 | Country record (USA)*, province record* | BC: WA, GA | Naturalist, BugGuide | JK |
| Graphogonalia cf. evagorata | Country record (USA) | TX | Naturalist | SH |
| Neocyrtia veracruzensis Dietrich and Dmitriev, 2007 | Country record (USA) | TX | Naturalist | CD |
| Tautoneura cf. polymitusa | Country record (USA)* | MO | Naturalist | SH |
| Erechta sp. | Country record (USA) | CA | Naturalist | SM |
| Phylla lownyi* Plummer, 1936 | Country records (USA) | AZ, NM | BugGuide | AH |
| Stictolobus borealis Caldwell, 1949 | Country record (USA), State records | ON, IA, IN, OH, PA, TN, VA | BugGuide, iNaturalist | SH |
| Telenora stephani Wallace, 2018  | State records, new species | FL, AL, CT, GA, MA, MO, NJ, NY, OH, RI, TN, WV | BugGuide, iNaturalist | KK, MW |
| Chloriona sicula Matsumura, 1910 | Country records (CAN, USA)* | ON, QC, MA, NY | BugGuide, Alusualist | CB |
| Tarophagus colocalosia Matsumura, 1932 | Country record (USA) | LA | Naturalist | CB |
| Anota firebuga Bahder and Bartlett, 2020 | Country record (USA) | TX | Naturalist* | BB |
| Issus coleopartus Fabricius, 1781 | Country record (USA) | BC | BugGuide* | JK |
| Metallomeracnus cf. leucodespixa | Country record (USA) | AZ | BugGuide | SH |

*There are no known published records of this species in North America, but JK has informed the authors that he has a collected specimen from Vancouver, British Columbia.

According to AH in a comment on BugGuide, there is a single specimen of this species in the Canadian National Collection that was collected from Arizona in 1998. However, this record is not noted in a comprehensive overview of the Neartic Treehopper fauna (Deitz and Wallace, 2012). Therefore, we are including this record in this table. State and Provincial abbreviations: AL = Alabama, AZ = Arizona, BC = British Columbia, CA = California, CT = Connecticut, FL = Florida, GA = Georgia, IA = Iowa, IN = Indiana, KY = Kentucky, LA = Louisiana, MA = Massachusetts, MD = Maryland, MI = Michigan, MO = Missouri, MS = Mississippi, NH = New Hampshire, NJ = New Jersey, NM = New Mexico, NY = New York, NC = North Carolina, OH = Ohio, OK = Oklahoma, ON = Ontario, OR = Oregon, PA = Pennsylvania, QC = Quebec, RI = Rhode Island, SC = South Carolina, TN = Tennessee, TX = Texas, UT = Utah, VA = Virginia, VT = Vermont, WA = Washington, WV = West Virginia.

Initial Identifiers: AH = Andy Hamilton; BB = Brian Bahder; CB = Charles Bartlett; CD = Chris Dietrich; CM = Chris Mallory; JK = Joel Kits; KK = Kyle Kittelberger; SH = Solomon Hendrix; SM = Stuart McKinney; VT = Vinton Thompson.
Records Database

The records in the *Hopper Site* database come from several main sources. Much of the data entered into the site originated from field surveys carried out by the first author visiting parks and other protected areas across the state between 2010 and 2020. The first author kept very detailed accounts of any diurnal or nocturnal surveys, recording the species found, numbers of each taxon present, habitat information, and, if applicable, host plant. The first author also submitted photographs and specimen information, such as sex and measurements, to go along with any of these submissions.

A large portion of the remaining records on the site originated from collections and the literature. The first author spent several months combing through pinned specimens in the NC State Insect Museum and incorporated all of these records into the *Hopper Site*. Other records were provided from two smaller in-state collections, from the Schiele Museum and lepidopterist J. B. Sullivan. The website iDigBio was also used to enter hoppers collected in-state but housed in facilities outside North Carolina. Other records were incorporated from various publications, particularly several comprehensive county-based checklists of treehoppers.

However, in an effort to have the records database be truly comprehensive and representative of the knowledge of species’ abundances and distributions in the state, and to take advantage of all types of documentation and knowledge contributions, the *Hopper Site* does not solely rely on personal and collection records. North Carolina State Parks (NC DPR) has its own state-wide inventory platform, the Natural Resources Inventory database (NRID), which NC DPR personnel use to submit records of biodiversity across state parks and natural areas. NRID is fully linked with the *Hopper Site* so that these records are automatically synced with the site. Perhaps most noteworthy, however, is the citizen science component of the

![FIGURE 3](image-url) | Noteworthy hopper species from continental North America that are mentioned in this study. (A) *Clastoptera octonotata* Hamilton, 2015- a spittlebug that was recently described and documented based on citizen science contributions ([Table 1](#)); (B) *Telamona stephani* Wallace, 2018- a recently described treehopper with first state records documented by citizen scientists ([Table 1](#)); (C) *Graphocephala hieroglifica* Say, 1830- a leafhopper that was first detected in North Carolina by citizen scientists ([Supplementary Table S3](#)); (D) *Allygus mixtus* Fabricius, 1794- an introduced leafhopper species that was first documented in Canada and rediscovered in Massachusetts by citizen scientists ([Supplementary Table S3](#)); (E) *Shellenius schellenbergii* Kirby, 1821- this infrequently encountered planthopper was first detected in North Carolina by citizen scientists ([Supplementary Table S3](#)); (F) *Chloriona sicula* Matsumura, 1910- an introduced planthopper that was first detected in the United States and Canada by citizen scientists ([Table 2](#)). All hoppers photographed by Kyle Kittelberger (A–C) or Solomon Hendrix (D–F).
A page devoted to hopper genitalia includes images of the ventral Carolina, with abundances in each of the three state regions noted. A complete checklist of the species currently known from North America is included, along with a detailed account of approaches to determining a species. The authors recommend, along with a detailed account of approaches to photographing individual hoppers.

Incorporating Citizen Science
Members of the public can contribute their own sightings to the Hopper Site by submitting records on the “Enter Record” page. There is a series of required information fields for the metadata of a record, such as location, date, email for correspondence, and the option to include other information such as plant associate and time of day. People are also required to upload at least one image to corroborate their sighting. If someone is unable to identify a hopper they have photographed, they can choose an unidentified option. These unidentified records can then be identified, if possible, by the site author, and the author will correspond with the contributor via their included email about these sightings.

These public records, along with those from NRID, are immediately quarantined to a section of the site that is only accessible to the administrators. These records are therefore not assimilated into the records database until being vetted by the site author. This approach helps filter records and prevent erroneous identifications from the public from being incorporated into the website. If an entry cannot be correctly identified to species level, the record is moved to a purgatory section of the site where it remains hidden from the public and does not factor into the website’s database.

Furthermore, records from BugGuide and iNaturalist are added to the database by the site author on a daily basis. While these websites can have issues when it comes to the accuracy of some species’ identifications and taxonomy, these challenges do not prevent these submissions to these sites from being valuable and informative. The site author vets any record from these two citizen science websites before entering them directly into the Hopper Site, noting the source of each sighting during record entry. With the incorporation of records from BugGuide and iNaturalist, all major sources of hopper records have been accounted for, ensuring that the Hopper Site database is comprehensive and reflective of what has been recorded in the state.

Citizen Science Recommendations
We first and foremost encourage researchers to become active in engaging with citizen scientists on various platforms. In the experience of KDK and SVH, engaging with the public helps foster their excitement to continue photographing, for example, hoppers, and we have observed many users choosing to photograph hoppers as a hobby. As the lead moderators of hoppers on BugGuide and iNaturalist over the last 7 years, KDK and SVH have developed numerous correspondences with BugGuide and iNaturalist contributors across North America and even beyond, with these users tagging or messaging us about their hopper sightings and asking for assistance with identifications.

Engaging with citizen scientists can also be instrumental to the accuracy of identifications and therefore the usability of these sightings in research (Wilson et al., 2020). We have the ability to easily correct or agree with identifications, particularly on iNaturalist, and taking time to vet records can make a significant difference in increasing the value of the data (Wilson et al., 2020). Users tend to be very receptive to having their identifications corrected, with many inquiring about what is needed to identify a hopper to species level. As
a result of KDK and SVH informing the public of whether photographs of the underside, measurements, or knowledge of the sex of a hopper are needed to make identifications for specific taxa, we have essentially trained some contributors to recognize these challenging taxa and therefore determine when they need to collect this additional information to assist with identification. Some citizen scientists have even learned to recognize when some taxa require dissection of a collected specimen to determine the species. This is highly important, as many hopper groups cannot be identified through photographs alone. Interacting with citizen scientists in this manner helps filter the noise from the plethora of uploads and strengthens the overall quality of the data.

Additionally, engaging with the public on these online platforms can be useful when a noteworthy taxon is found, whether a state or country record, a potentially undescribed species, an unknown nymph, or a poorly known and infrequently encountered species with little to no prior available photographic documentation online. Not only are we able to recognize when a hopper may be something special, but we are also able to instruct citizen scientists on how to proceed with documenting these records. Through our correspondences we have had a number of people either take additional photographs or provide information such as the host plant of what might be noteworthy records. In some cases, people have collected specimens for us or our contacts. While many hoppers can indeed be identified from pictures alone and therefore do not require being collected, our interactions with hopper enthusiasts can help lead to selective collecting when appropriate. For example, the first author noticed a series of photographs on iNaturalist of a strange Clastoptera species from Louisiana and asked the observer to collect and send off several specimens for dissection; initial analysis of the specimens suggests that this is an undescribed species (Supplementary Table S2).

We also emphasize that these engagements and contributions of citizen scientists and citizen science platforms be properly recognized in the literature (Wilson et al., 2020), as a majority of citizen-science collected data does not get referenced in peer-reviewed literature (Theobald et al., 2015). For one state record in the literature (Leavengood et al., 2017), which was first posted by a user on BugGuide (Asarcopus palmarum in Texas), the online platform was not mentioned in the publication. While the person that found the record was included as an author in the paper, we suggest that the online source of the record also be included in these kinds of publications (see other literature in Table 1) in order to help recognize the value of these citizen science platforms in entomology.

We also recommend that researchers develop better approaches to disseminating knowledge and expertise to the general public. Some of this dissemination can come through interactions online with citizen scientists, or even by contributing knowledge to the “Info” pages on BugGuide (see Methods, Citizen Science Background). Unlike charismatic biodiversity such as birds or even butterflies and odonates, much of the literature on hoppers remains scattered and hard to access, and most species lack high quality and/or correctly identified photographs online. Therefore, we stress the need for the development of photographic libraries of different species, particularly of specimens representing infrequently and poorly known species. The Hopper Site serves as a great example of what can be possible in addressing these issues, with a layout that effectively disseminates knowledge from the literature and displays multiple photographs of species that can aid the public in identification of different sexes, forms, subspecies, and life stages of species.
Finally, as with any form of citizen science, there is a certain inevitability for inaccuracies and an overzealous pursuit of precision without intervention. As mentioned earlier, the engagement of researchers can help to mitigate this, but there are also actions that citizen science websites can take to ensure more accurate and scientifically useful results. First of all, we recommend that citizen science sites discourage users from making initial species-level identification without input from a knowledgeable expert, especially for challenging arthropod taxa. Likewise, we recommend sites diverge away from the recent inclination to use AI to make species-specific identification beyond family-level; we have seen firsthand on iNaturalist that the AI is just too inaccurate for many hoppers and it often leads to misidentifications, even when drawing from larger datasets. Sites should also verify experts through a simple review of credentials, and experts should consequently make their knowledge and area of expertise clear through their site profiles. We also encourage platforms to increase the number of default fields for data entry, such as size, plant/animal association, quantity observed, and habitat (see Hopper Site) to ensure more accurate identifications of arthropods. Lastly, we recommend that these sites create designated areas for the clear and concise relay of important information regarding identification. Such an area of the site should be foremost for each taxon and immediately accessible to any user, with clear information about how to differentiate very similar taxa (see Hopper Site).

DISCUSSION

Citizen science can play an especially important role in advancing the research and monitoring of under-studied biodiversity (Amano et al., 2016; Chandler et al., 2017; Theobald et al., 2015), particularly arthropod taxa such as hoppers. At a time when there is increasing concern among entomologists about a significant global decline of insects (Montgomery et al., 2020; Wagner et al., 2021), citizen science can be effective in monitoring insect populations on as wide a scale as possible, while also affording copious sample locations and coverage that even the most extensive studies would struggle to replicate. Being a suborder of one of the most diverse and speciose insect orders in the world, while also in great need of further study, makes Auchenorrhyncha an optimal candidate for this analysis.

Contributions from citizen scientists are also leading to important discoveries of both described and undescribed species that help increase our knowledge of the natural world. We found 11 publications that mentioned country records, state records, or recently described hopper species for 18 taxa that were found and documented by North American citizen scientists (Table 1), with a couple of other publications noting contributions of citizen scientists towards an improved understanding of the natural and evolutionary history of Auchenorrhyncha (Hamilton, 2011, 2012). In comparison, there are notable first country or state records of 24 taxa submitted to BugGuide and iNaturalist that have not yet been recognized in the literature (Table 2). We also have compiled a list of undescribed or potentially undescribed hopper taxa that were discovered and documented by the public (Supplementary Table S2), helping underscore the value of citizen science contributions to the study of Auchenorrhyncha. Furthermore, within the last 2 decades, the number of photographic hopper observations posted online by citizen scientists has exponentially grown annually (Figure 2) and is equivalent to approximately 58% of all hopper specimens in digitized collections in continental North America (Figure 1), emphasizing the impressive spatial and temporal scale of data collection by members of the public. Additionally, we show that accelerating growth in citizen science data collection in recent years is not restricted to just birds (Amano et al., 2016), as there is a clear acceleration in enthusiasm by the general public photographing and uploading sightings of hoppers in at least North America (Figure 2).

In North Carolina alone, submissions by the public have greatly expanded the knowledge of hopper distribution and abundance in the state, with hundreds to thousands of county records (Kittelberger and Howard, 2021) and 53 first state records since 2008 (Supplementary Table S3). The invaluable contributions of the public to helping provide a much better understanding of the number of hopper species that occur in North Carolina serves as a microcosm for the important hopper documentations people are making in the rest of North America. Furthermore, citizen science records on these platforms have helped confirm the presence of previously published records in parts of North America, sometimes many decades after the last reported sighting or collection date. For example, the leafhopper *Allyus mixtus* (Figure 3D) was recorded from Massachusetts in 1919 and subsequently assumed to have died out after no new records had been reported for almost a century (Hamilton, 1983). However, the species was rediscovered in the state in 2017 based on BugGuide records.

Data from citizen science records has also provided us with information pertaining to large range expansions of both native and introduced species. The adventive *Curtara insularis* (Table 2), officially recorded in Florida in 2009 (Halbert, 2009) and subsequently found in BugGuide records for the state dating back to 2004, has experienced a rapid range expansion throughout the southern United States and into Nearctic Mexico within the past several years (i.e., first recorded in North Carolina in 2017). While this massive expansion seems to have evaded the scientific press for over a decade, the current distribution of the species is quite evident through citizen science records. *Pagaronia minor*, introduced from Japan and first discovered in North America in New York in 2005 (Hamilton, 2011), has also seen a fairly rapid range expansion in recent years, now ranging south into the mountains of North Carolina (first record in 2014). Likewise, the introduced African planthopper *Tarophagus colocasiae* recently expanded west from Florida into Louisiana and is now well established in the coastal part of the state (Table 2).

The citizen scientists that share observations from either side of the United States-Mexican border are also of great benefit to the entomological community, and many country records and potentially new species have been recorded by photographers...
near the border (Table 2). People in the southernmost regions of Texas have obtained many new records for the United States, including Aeneolamia contigua, Cephus cf. brevipennis, Anotia firebugia, Egidemia cf. inflata, and Graphogonalia cf. evagorata (Table 2). Some of these records are somewhat predictable occurrences based on known ranges (Aeneolamia contigua, Graphogonalia cf. evagorata) while others are rather notable jumps from previously known ranges (Anotia firebugia, Egidemia cf. inflata). Across the border in Mexico, citizen science records on iNaturalist can offer insight into potential future additions to the North American hopper fauna. These potential future records by means of northward range expansion could include Apogonalia monticola, Draeculacephala dypeata, Draeculacephala soluta, Oncometopia clarior, and Paraulacizes thunbergi.

While the focus of our study is on the United States and Canada, we found many references to citizen science contributions in hopper papers outside North America, especially in regards to iNaturalist in Europe. For example, iNaturalist has been instrumental in tracking the spread of the planthopper Acanalonia conica throughout the Western Palearctic (Holzinger et al., 2020; Pélozuelo et al., 2020). The global focus of iNaturalist is crucial to understanding the spread of certain problematic species that have a high risk of spreading worldwide, such as the highly destructive Spotted Lanternfly (Lycorma delicatula) in the Eastern United States. Observers within the past 2 years have also discovered the likely presence of the Korean Typhlocybine leafhopper Tauntona polymitusa in Missouri (Table 2) as well as in various countries in the Western Palearctic (Tóth et al., 2017; Gubin et al., 2020; Kosovac et al., 2020), indicating a new and poorly-known introduction to temperate regions. Catching these sudden introductions of species before they become well established and verifying their presence is crucial to preventing significant ecological and economic damage in the future.

As the number of people contributing to citizen science continues to rapidly expand (Figure 2), it is important to capitalize on the growing value of the entomological curiosity shared by these amateur naturalists, particularly the younger generations (Generations Y and Z) of contributors to sites such as iNaturalist which tend to have a preference towards the younger generations (Y and Z) of contributors to sites shared by these amateur naturalists, particularly the younger generations. The entomological curiosity capitalized on the growing value of the entomological curiosity may continue to grow as the platform and its impact extend further (Figure 2).

We have provided a series of recommendations in this paper to the entomological community on how to approach data collected through citizen science. Not only can experts support and help foster passions to document nature through correspondences with the general public, but we can play an important role in the curation of data by providing and vetting identifications of observations submitted to platforms such as BugGuide and iNaturalist. We have the ability to help teach amateur naturalists how to properly document various species for identification purposes by informing them when details such as appropriate morphometric information or photographic angles are needed to make a species identification. Likewise, we can use this passive surveillance of arthropods to ask people to selectively collect specimens to aid our efforts to catalog the entomological world. However, we also believe that citizen science websites can help play an important role in ensuring a higher standard of data submitted by the public, through efforts such as moving away from a reliance on artificial intelligence. With a proper understanding of how to distinguish between species and noting what identification challenges exist for specific taxa, it is possible to use digital photography and the contributions of citizen scientists to advance our knowledge of the biogeography and natural history of arthropods (Goufla et al., 2013).

Finally, we believe that the Hoppers of North Carolina website is a revolutionary tool for identifying hoppers, serving as the most comprehensive and informative website covering any state’s hopper fauna in the United States. It has a modernized approach to identifying these insects, with a focus on disseminating knowledge of these taxa to the public and guiding users through hoppers and how to identify them (Kittelberger and Howard, 2021). The site incorporates information from hundreds of publications and taxonomic sites, information that is not necessarily easily accessible or well known to the general public. It also has amalgamated records from a variety of sources, including BugGuide, iNaturalist, and iDigBio, ensuring that it is as authoritative as possible in representing the knowledge of any spittlebug, leafhopper, treehopper, or planthopper found in the state. The Hoppers of North Carolina site can help serve as a model for current and future websites that function as interactive photographic field guides, records databases, and citizen science platforms—not only for Auchenorrhyncha but for arthropods and other lesser-known taxa.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KK and SH wrote the manuscript, with input from ÇS; KK conceived the original idea for the paper; KK conceived the idea behind and is the author of Hoppers of North Carolina, for which KK also acquired funding and resources; KK and SH compiled the data for this paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.710396/full#supplementary-material.

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