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# The power of citizen science to advance fungal conservation

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**Abstract**

48  Fungal conservation is gaining momentum globally, but many challenges remain. To
49  advance further, more data are needed on fungal diversity across space and time.
50  Fundamental information regarding population sizes, trends, and geographic ranges is also
51  critical to accurately assess the extinction risk of individual species. However, obtaining
52  these data is particularly difficult for fungi due to their immense diversity, complex and
53  problematic taxonomy, and cryptic nature. This paper explores how citizen science projects
54  can be leveraged to advance fungal conservation efforts. We present several examples of
55  past and ongoing citizen science-based projects to record and monitor fungal diversity.
56  These include projects that are part of broad collecting schemes, those that provide
57  participants with targeted sampling methods, and those whereby participants collect
58  environmental samples from which fungi can be obtained. We also examine challenges and
59  solutions for how such projects can capture fungal diversity, estimate species absences,
60  broaden participation, improve data curation, and translate resulting data into actionable
61  conservation measures. Finally, we close the paper with a call for professional mycologists
62  to engage with amateurs and local communities, presenting a framework to determine
63  whether a given project would likely to benefit from participation by citizen scientists.
64
67
68  **1 INTRODUCTION**
69  Citizen science (CS) consists of engaging the public in research practice and scientific
70  knowledge generation, empowering non-scientists to generate reliable data that can be used
71  by academics, policymakers, and other stakeholders (Miller-Rushing et al., 2012). Although
72  such non-experts have contributed to scientific discourse for centuries (Silvertown, 2009;
73  Miller-Rushing et al. 2012), the term "citizen science" first appeared only in 1989. Kerson
74  (1989) provided a preliminary description of the practice of generating data through the
75  engagement of non-expert volunteers and non-professional scientists (e.g., amateur
76  naturalists) in order to address politically or socially relevant issues. This concept has since
77  evolved so rapidly that today it has become difficult to provide a single definition (Haklay et
78  al., 2021). Here, we use the term to refer to public engagement in scientific research, in
79  which community members actively contribute to science either intellectually or with tools
80  and resources.
81
82  The growth of CS has been fostered by emerging information technologies and social media
83  platforms that have significantly simplified data acquisition and data transfer between
84  involved parties (Newman et al., 2012). These modern technologies present opportunities to
85  further democratize science by providing non-experts access to scientific information and
86  promoting global information-sharing among amateurs and professionals. Indeed, among the
87  major advantages of CS is that individuals with varying levels of expertise, ability, and time
88  can participate (Irga et al. 2020).
89
90  CS projects are becoming increasingly utilized in various scientific fields such as medicine,
91  ecology, meteorology, and public health (Lewandowski et al., 2017) and are an increasingly
92  powerful means to collect diverse forms of biological data (Bonney, 2021; Silvertown, 2009).
93  These data have been used to explore biological questions related to species distributions
94  (e.g., van Strien et al., 2013), demographic trends (Horns et al., 2018), the spread of
95  invasive species (Brown et al., 2001), and the value of ecosystem services (Harrison et al.,

96    2020). In mycology, CS initiatives are helping to address specific challenges such as high
97    species diversity, unresolved taxonomy, and conservation (Heilmann-Clausen et al., 2019;
98    Koukol et al., 2020; Polemis et al., 2023). In this review, we summarize the achievements of
99    CS in the study of fungal diversity to date and explore possible future applications. We also
100   highlight key challenges to CS and discuss ways to overcome them.

**2 HARNESSING CITIZEN SCIENCE TO ADVANCE FUNGAL CONSERVATION**

103   Fungi are ubiquitous and fulfill diverse ecological roles. They are involved in countless
104   interactions with other organisms, including plants, animals, bacteria, protists, and other
105   fungi. Although the estimated number of fungal species is approximately 2.5 million
106   (Niskanen et al., 2023), only around 154,000 are currently described (Bánki et al., 2023).
107   This biological knowledge shortfall has impeded global fungal conservation efforts across
108   different scales (Hortal et al., 2015). Current biological conservation frameworks depend on
109   observation and data collection. Thanks to molecular data, our capacity to monitor fungal
110   biodiversity has expanded to include poorly studied taxa that have historically been
111   overlooked with traditional field-based observations (Cazabonne et al., 2022). Despite this
112   progress, our understanding of these groups remains limited by a lack of sampling across
113   time and geography (Halme et al., 2012) (Figure 1).

115   Notwithstanding these gaps in knowledge, fungal conservation has gained momentum. The
116   FF&F initiative, adding the term funga to be used alongside fauna and flora (Kuhar et al.,
117   2018), aims to write fungi into conservation and agricultural policy frameworks, and unlock
118   funding for mycological research, surveys, and educational programs. Chile became the first
119   country to specify that fungi should be included in formal conservation and management
120   policy (República de Chile, 2010). Another milestone was the publication of open letters
121   calling on policymakers to include all fungi in global biodiversity targets (Gonçalves et al.,
122   2021) and acknowledge their roles in ecosystems (Palahí et al., 2022). Finally, an
123   unequivocal mark of progress is the sharp increase in the number of assessed fungal
124   species on the IUCN Red List of Threatened Species (hereafter the Red List) (Mueller et al.,
125   2022), which grew from two in 2003 to 625 as of 27 June 2023 (IUCN, 2023).

127   Despite these advances, fungal conservation continues to face challenges. First, relative to
128   many other taxa, fungi are often neglected in biological research due to their cryptic nature
129   (Rambold et al., 2013). As such, the number of Red List assessments of fungi pales in
130   comparison to other multicellular organisms (Figure 2). As of 27 June 2023, 87,082 animal
131   species and 62,666 plant species have been assessed by the IUCN (2023), compared to
132   just 625 fungi. Second, within fungi, there is a research bias towards groups that produce
133   macroscopic fruiting bodies (Gonçalves et al., 2021). Third, given the multitude of their
134   interactions, fungal conservation efforts inherently necessitate the conservation of their
135   associated organisms, adding further complexity to these efforts (Tylianakis et al., 2010).
136   Finally, there remains a lack of resources and personnel for expert-led fieldwork surveys – a
137   trend that may intensify given the decline in prioritization of field-based studies amongst
138   conservation scientists (Ríos-Saldaña et al., 2018).

140   One way to overcome these challenges and address fundamental issues in fungal
141   conservation is to leverage CS-sourced data (Heilmann-Clausen et al. 2019). Projects
142   involving local communities and amateur mycologists are becoming more popular as the
143   scientific value of data collected by non-professionals is increasingly recognized (Silvertown,

144 2009). Given the limited number of professional mycologists and funding resources,
145 opportunities exist for members of the public to provide significant contributions in
146 accumulating large amounts of data in a short period (Gryzenhout, 2015). Amateur
147 observers have the potential to generate numerous fungal records, including those of
148 undescribed and endangered species that can be used to inform fungal conservation efforts
149 (Irga et al., 2020).
150
151 Even small-scale CS efforts in mycology can provide valuable insights into fungal species
152 distributions and ecological interactions by gathering images and mapping species
153 occurrences (e.g., Heilmann-Clausen et al., 2016; Shumskaya et al., 2023). Amateur
154 mycologists are often among the only sources of data collection in under-documented
155 regions. Furthermore, interested amateurs could assist in searching for rare species under
156 professional scientific guidance and discovering fungal species new to science (e.g., Crous
157 et al., 2017, 2021).
158
159 **3 EXAMPLES OF ONLINE DATABASES AND FUNGAL CITIZEN SCIENCE PROJECTS**
160 In this section, we present the primary online databases used for data collation and several
161 examples of fungal CS initiatives to showcase how they can be planned, structured, and
162 used. While not a comprehensive list, these examples illustrate the potential of CS-
163 generated datasets to examine fungal biodiversity trends and distributions across
164 landscapes and time. We categorize projects by organizational structure: unstructured
165 projects, targeted approaches, and derived projects.
166
167 *Online databases*
168 Digital occurrence data can be gathered on a large scale using online repositories. Such
169 tools can be very powerful with respect to observing distribution patterns. While some
170 projects have developed their own specific repositories, iNaturalist and MushroomObserver
171 are the most widely used CS online databases in mycology.
172
173 iNaturalist (https://www.inaturalist.org/) is an online CS platform that depends on community
174 identification of submitted records. Anyone globally can submit observations, usually images
175 of an organism taken in the field. The platform can suggest identifications based on a
176 computer vision model. However, only those observations with sufficient metadata and
177 identifications confirmed by other users are considered "research grade". This not only
178 encourages users to interact with each other but also functions as a quality filter (Hiller &
179 Haelewaters, 2019). The value of such records to conservation relies on their volume and
180 accessibility; all that is needed to contribute is a suitable device and internet access.
181 Projects can be created on iNaturalist to aggregate observations based on specific criteria
182 such as location and taxon. For example, iNaturalist data have been used to reevaluate the
183 common discomycete genus *Bisporella* (Mitchell et al., 2022) and to update the geographical
184 distribution of the biotrophic microfungus *Hesperomyces harmoniae* (de Groot et al., in
185 review). As of 28 June 2023, iNaturalist has recorded 8,741,713 observations representing
186 20,096 species of fungi submitted by 651,795 contributors.
187
188 Before the existence of iNaturalist, MushroomObserver (https://mushroomobserver.org/)
189 served as the primary international platform for recording CS fungal observations online. It is
190 still used by citizen scientists for recording sightings, publishing images, and identifying
191 fungi. Thus far, MushroomObserver collates 480,069 observations representing 18,923 taxa

192 recorded by 11,641 contributors. Professional mycologists using these online CS databases
193 can access huge amounts of data; for example, Bazzicalupo et al. (2022) calculated that
194 iNaturalist and MushroomObserver combined have resulted in over 500,000 CS
195 observations of fungi in Canada alone.
196
197 The Global Biodiversity Information Facility (GBIF, https://www.gbif.org) is an open-access
198 platform that aggregates occurrence records from multiple sources. "Research grade"
199 observations from iNaturalist are automatically uploaded to GBIF. Records from specific CS
200 projects (see below) and fungaria can also be submitted to GBIF. These CS observations
201 are then made more widely available for scientific use and increase the completeness of
202 species distribution maps needed for conservation work.
203
204 *Unstructured projects*
205 Unstructured CS projects form part of broad recording schemes. These projects aggregate
206 observations through online databases, by digitizing foray collections, or from dried
207 specimens sent to professional mycologists for validation. Below, we present several CS
208 projects, from the local up to the continental scale.
209
210 To map fungal diversity in and around the city of Coimbra, Portugal, the local CS project
211 Cogumelos na Cidade (Mushrooms in the City) uses iNaturalist's 'Projects' tool as a platform
212 (https://www.inaturalist.org/projects/cogumelos-na-cidade). As of 28 June 2023, 148
213 contributors have contributed 2,232 observations, representing 365 species of which 223 are
214 "research grade."  Although only started in September 2020, this project has already resulted
215 in the identification of new records for Portugal and helped document the presence and
216 spread of exotic species. Vouchers for several of these observations await identification and
217 will likely contribute to additional new and rare species for Portugal.
218
219 The New Jersey Mycological Association collections from regional forays over 12 years were
220 collated into a dataset containing 400,260 occurrences of 1,483 species (Shumskaya et al.,
221 2023). Approximately 3,000 specimens are curated in a private herbarium at Rutgers
222 University. The database is georeferenced and accessible through GBIF.
223
224 The MIND.Funga App (https://mindfunga.ufsc.br/app/?lang=en) is the latest development of
225 a regional CS project that was started in 2020 in southern Brazil to record occurrences of
226 fungal species with images and associated metadata. It represents a tool for macrofungal
227 recognition based on submitted images, identified using a deep learning neural network
228 model. Species names are suggested with a confidence rating. Thus far, the MIND.Funga
229 App has received 17,467 images representing more than 500 species (Drechsler-Santos et
230 al., 2023).
231
232 The Danish Fungal Atlas (https://svampe.databasen.org/en/) is a national CS project aiming
233 to build a checklist of macrofungi in Denmark. Any individual can submit data on location and
234 associated organisms of rare and common fungi. Records are cross-referenced with GBIF.
235 In total, 5,014 observers have contributed 1,109,146 expert-validated records, representing
236 9,081 species. Of those, 15 were new to science and 197 were new records for Denmark
237 (Heilmann-Clausen et al., 2019). Several research papers have used these data to explore
238 subjects such as host selection in wood-inhabiting fungi (Heilmann-Clausen et al., 2016),
239 biases in recording schemes in CS (Geldmann et al., 2016), and biodiversity patterns

240    (Andrew et al., 2018). This project has also informed systematic conservation planning in
241    Denmark (Petersen et al., 2016) and supported the development of AI-based identification
242    tools (Picek et al., 2022).
243
244    The "Mushrooms of Kenya" project was initiated in 2019 to create awareness about fungi
245    among local communities and conservationists, develop a countrywide field guide, and
246    improve understanding of fungal distribution patterns. An iNaturalist project
247    (https://www.inaturalist.org/projects/mushrooms-of-kenya) was created to collect
248    observations of macrofungi in Kenya. As of 28 June 2023, 294 contributors have made
249    4,240 observations, representing 424 species. In addition, 3,488 specimens are being
250    maintained at the East African Herbarium, National Museums of Kenya. The project has an
251    educational program that equips CS participants with training in macrofungal sampling,
252    preservation, and identification.
253
254    Fungimap (https://fungimap.org.au/) is an Australian CS organization hosting an iNaturalist
255    project (https://inaturalist.ala.org.au/projects/fungimap-australia) with 90,386 observations
256    representing 1,768 species recorded by 914 contributors, as of 28 June 2023. The National
257    Australian Fungimap Database was established to track rare and threatened species and
258    currently has more than 100,000 records provided by 1,000 contributors. Fungimap also
259    collaborates with BioSMART to host the Great Aussie Fungi Quest
260    (https://www.biosmart.life/australian-fungi-quest-2023). This is an annual event similar to the
261    Great North American Fungi Quest, but only runs on two apps: QuestaGame.com and
262    iNaturalist.org. As of 28 June 2023, 13,309 observations representing 1,131 species were
263    recorded by 1,973 contributors.
264
265    Finally, as an example of a continental CS project, the Great North American Fungi Quest is
266    a month-long fungal survey (https://www.biosmart.life/north-america-fungi-quest-2022).
267    Participants submit observations through one of six CS apps: iNaturalist.org,
268    MushroomObserver.org, Observation.org, Questagame.com, NatureSpots.net, and
269    CitSci.org. Aggregating data from multiple apps increased accessibility, which resulted in
270    157,701 observations representing 7,612 species recorded by 34,532 people in 2022.
271
272    *Structured approaches*
273    Structured CS projects provide participants with targeted sampling approaches, protocols, or
274    species lists. Advantages of such projects include allowing researchers to streamline data
275    collection toward addressing specific questions, challenges, and conservation goals.
276    Examples of structured projects include the FunDiS Rare Challenges, Lost and Found Fungi,
277    and the Distribution Research Forest Mushrooms of the Dutch Mycological Society.
278
279    The Fungal Diversity Survey (FunDiS) hosts a biodiversity database through iNaturalist
280    (https://www.inaturalist.org/projects/fundis-biodiversity-database) and has launched several
281    Rare Challenges (https://fundis.org/protect) to document rare and threatened fungi from a list
282    of target taxa in specific geographic areas. FunDiS makes posters and pamphlets available
283    to participants of Rare Challenges, with relevant information about target taxa, such as
284    preferred habitat, seasonality, potential range, and similar-looking species. The West Coast
285    Rare Fungi Challenge focuses on 20 species of macrofungi and since its inception in
286    October 2020 has amassed 681 observations representing 16 species submitted by 388
287    contributors. Thus far, different FunDiS initiatives have resulted in 183,932 observations in

288  iNaturalist representing 5,691 species submitted by 1,425 contributors as of 8 November
289  2023.
290
291  The Lost and Found Fungi (LAFF) project (https://fungi.myspecies.info/content/lost-and-
292  found-fungi-project) was hosted by the Royal Botanic Garden, Kew from 2014 to 2019 to
293  produce a dataset of occurrences for rare target species not observed for ≥50 years.
294  Records taken from the literature and fungaria were supplemented by submissions from
295  citizen scientists. This project resulted in approximately 1,400 new records representing 77
296  species and facilitated Red List assessments of 20 target species.
297
298  The Dutch Ecological Monitoring Network (https://www.netwerkecologischemonitoring.nl/) is
299  government-run and has programs across organismal fields, including the Mushroom
300  Monitoring Program (Meetnet Paddenstoelen) of the Dutch Mycological Society. It consists
301  of three different projects, for which volunteers collect data. Since 1998, the
302  Verspreidingsonderzoek Bospaddenstoelen (Forest Mushrooms Distribution Research) aims
303  to document 138 typical species annually in forests on sandy soils and dunes
304  (https://www.verspreidingsatlas.nl/projecten/nmv/bospaddenstoelen/). Each 1×1 km$^2$ plot is
305  monitored three times annually, with participants recording all mushrooms observed along a
306  fixed 0.5–1.0 km-long transect as well as corresponding metadata. Expert users verify all
307  submitted observations.
308
309  *Derived projects*
310  Another way to involve CS participants in gathering fungal biodiversity data is to have them
311  submit environmental (i.e., non-fruiting body) samples from which fungi can be obtained or
312  sequenced. These so-called derived projects require extra steps by professional mycologists
313  to "derive" fungal biomass or sequences from the samples. One example is the Dutch
314  garden soil school project "Wereldfaam, een schimmel met je eigen naam" (World fame, a
315  fungus with your name). It used 404 soil samples submitted by children to obtain 4,750
316  fungal isolates and has thus far resulted in the description of two new genera and 24 new
317  species of Zygomycota, Dothideomycetes, Eurotiomycetes, and Sordariomycetes (Crous et
318  al., 2017, 2021; Hou et al., 2020). A second example is FunLeaf
319  (https://sisu.ut.ee/funleaf/about) which seeks to describe global leaf endophyte communities
320  using leaves submitted by CS participants. Detailed protocols are provided for submission
321  and all data are made available to participants through the PlutoF Biodiversity Platform
322  (https://plutof.ut.ee/).
323
324  **4 CHALLENGES AND SOLUTIONS**
325  CS is uniquely positioned to capture biodiversity data across spatial, temporal, and
326  taxonomic axes on a scale often unachievable for professionals. Indeed, the above
327  examples showcase evidence that CS is producing useful output for mycologists. However,
328  to truly harness the power of CS to advance fungal conservation, a number of obstacles
329  spanning data curation to community engagement must be addressed. Here, we present five
330  challenges and provide recommendations to improve the utility and impact of CS for fungal
331  conservation.
332
333  *Capturing fungal diversity*
334  One of the greatest challenges in CS is how to overcome taxonomic biases, particularly
335  concerning fungi that are cryptic, ephemeral, and speciose. Public records are heavily

336 biased by organismal preference (Figure 1). Most CS projects focus on large, easily
337 identifiable sporocarps, and as such document only a fraction of extant fungal diversity. CS
338 projects targeting microfungi, by contrast, need to provide advanced training and equipment
339 because these fungi are difficult for non-specialists to find and identify. Similarly, fungi
340 requiring microscopy and chemical testing for proper identification are a challenge for
341 inclusion in CS projects. As an example, McMullin & Allen (2022) found that the proportion of
342 accurate identification of lichen species on iNaturalist.org was 59% when only
343 macromorphology was needed, but dropped to as low as 5% when further analyses were
344 required.
345
346 Targeted projects can increase awareness and appreciation of understudied fungal groups.
347 Successful targeted projects have resulted in many scientific contributions, including the
348 identification of new species (Koukol et al., 2020) and insights into how environmental
349 contamination may affect the development of endangered fungal species (Irga et al., 2018).
350 CS participant-led initiatives, such as the Welsh Microfungi Group, have built interest and
351 momentum around documenting underappreciated fungal groups, including microfungi and
352 pathogens, such as downy mildews and parasitic hyphomycetes (Chater et al., 2021).
353
354 To minimize low-confidence observations, experts could pre-identify which species require
355 information beyond a macroscopic image. Taxa requiring microscopy, DNA, or host
356 information for an accurate identification could be indicated in CS repositories. Observers of
357 these species would then need to indicate whether specialized data beyond macroscopic
358 images were supplied. Observations lacking these specialized data would not be considered
359 "research grade." Professional mycologists can also play a crucial role as identifiers on CS
360 platforms by helping to identify and comment on observations made by other users or
361 downgrading observations not meeting the needed criteria.
362
363 To identify difficult species, CS participants may benefit from automated image recognition
364 models, used in platforms such as iNaturalist, although these still have limitations. The
365 accuracy of machine learning (ML) models is predicated on training data and requires
366 sufficient and accurate examples (Picek et al., 2022). ML-based identification therefore risks
367 perpetuating inaccurate identifications if based on biased input samples, and likely makes
368 automated image identification less useful for under-sampled taxa (Koch et al., 2022).
369 Because ML models depend on the presence of distinguishing features, species that lack
370 identifiable characters can confound accurate identification for CS participants and ML
371 models alike. Nevertheless, ML has great potential, and the increased availability of
372 benchmarked training data along with the proliferation of new, increasingly complex models
373 are expected to improve the utility of ML in species identification.
374
375 Finally, environmental DNA (eDNA) approaches can be more sensitive in capturing total
376 fungal diversity than those based on sampling individual fruiting bodies (Nilsson et al., 2019;
377 Shirouzu et al., 2020), although using eDNA has its own caveats (Carini et al., 2016).
378 Projects utilizing CS participants to gather environmental samples, such as soil, litter, wood,
379 and other plant material, for eDNA extraction and analysis are well poised to help capture a
380 more complete view of fungal biodiversity. The FunLeaf project, mentioned above, is one
381 example already employing CS in these efforts.
382
383 *Estimating species absences*

384    An important element in assessing biodiversity for conservation is our ability to identify
385    where species are truly absent (Martin et al., 2023). Although presence-only data is widely
386    considered to be inferior to presence–absence data for determining species distributions
387    (Johnston et al., 2021), proving true absence is more difficult than proving presence,
388    particularly in cryptic taxonomic groups (e.g., Haelewaters et al., 2023; Kéry, 2002). As such,
389    current fungal repositories and datasets consist almost exclusively of presence-only
390    observations.
391
392    CS fungal repositories could aid in tracking absence data by incorporating the ability to state
393    whether the submitted observation is part of a "complete list" of all fungi found for the
394    location visited, as is currently possible in eBird and eButterfly (Johnston et al., 2021; Prudic
395    et al., 2017). Ideally, such a feature would allow for editable definitions of what a "complete
396    list" entails based on individual sampling schemes (for example, allowing users to state that
397    they recorded all poroid fungi on woody substrates over 1 cm in diameter). For complete
398    lists, a function for reporting effort (such as time spent and number and experience level of
399    participants) would further enable confidence scoring both presence and absence data
400    (Johnston et al., 2021; Picek et al., 2022).
401
402    Structured projects can help to document absences by arming CS participants with informed
403    search lists for target species—a concept that has also been applied to other taxa (Martin et
404    al., 2023). The continued absence of taxa, even after targeted search campaigns, adds to
405    our understanding of true absence and species rarity. This was the case for *Hypocreopsis*
406    *amplectens*, now considered critically endangered. Researchers were able to nominate the
407    species for protective status after it spent many years on the 100-species Fungimap target
408    list, and yielded only 13 observations (Buchanan & May, 2019). It should be noted that
409    absence-only data can also be a valuable contribution to conservation. After Sweden's ash
410    populations were devastated by the fungus *Hymenoscyphus fraxineus*, the Rädda Asken
411    (Save the Ash) CS program was created to locate healthy trees that lacked signs of *H.*
412    *fraxineus* infection, successfully identifying hundreds of genotypes for resistance breeding
413    (https://raddaasken.nu/en/home; Hulbert et al., 2023).
414
415    Recording and monitoring fungal distributions and rarity are complicated by the phenology of
416    fruiting (which may occur seasonally) and ephemerality of fungi and their substrates
417    (Straatsma et al., 2001). When fruiting of a given species does not occur year-round or every
418    year, absences of that species in CS projects may be difficult to interpret. The ephemeral
419    nature of sporocarps also represents a challenge when recording diversity (Cazabonne et
420    al., 2022; Kauserud et al., 2008), exacerbated when hosts or habitats are ephemeral
421    themselves. Examples of this include species of *Hypomyces* that parasitize mushrooms in
422    Agaricales (Rogerson & Samuels, 1994) and *Pyxidiophora* that parasitize fungi growing on
423    herbivore dung and decomposing plant materials (Haelewaters et al., 2021). Finally, ease of
424    access to collection sites is another factor adding geospatial bias to observation datasets.
425    For example, on large scales, CS projects tend to source more data from non-tropical
426    countries (and more accessible and densely populated parts of non-tropical countries (Tiago
427    et al., 2017) while on more local scales sampling is often concentrated around easily
428    accessible trails (Mandeville et al., 2022).
429
430    *Broadening participation*

431    Ensuring CS participation from people with a diversity of backgrounds is critical to both
432    equitable community engagement and unlocking the full potential of CS to inform fungal
433    conservation. Recruiting and retaining participants from diverse backgrounds can help fill
434    geospatial gaps, provide experts with knowledge of endemic taxa, and increase the
435    investment of various people and communities interested in fungal conservation. Unequal
436    engagement across socioeconomic and sociopolitical axes currently leads to
437    overrepresentation of sampling in North America, Europe, and Australia, while leaving taxa
438    in vast stretches of the world under-reported and under-characterized (Lofgren & Stajich,
439    2021; Quandt & Haelewaters, 2021). Gaps in CS engagement currently mean lower
440    participation among people of color, women, and low-income earners (Pateman et al., 2021).
441    Developing strategies toward broader engagement should be a priority for the field.
442
443    Day et al. (2022) found that enthusiasm to engage in future conservation efforts is only
444    expressed in participants who feel they made a significant contribution to a CS project. In
445    this way, project assessment and reporting are critical to repeated engagement and
446    improving the design of future programs. In summary, CS projects should: 1) clearly and
447    continuously communicate project goals, 2) strive for diverse representation among leaders
448    and participants, 3) account for participant experience level, 4) provide various engagement
449    opportunities for people experiencing different motivations and barriers, 5) share final project
450    results with participants, 6) obtain feedback from CS participants, and 7) publish a formal
451    report on participant assessments (Cheeke et al., 2018; Estes-Zumpf et al., 2022; Jordan et
452    al., 2012; Lofgren & Stajich, 2021; Kaplan Mintz et al., 2023).
453
454    *Improving data curation*
455    Hundreds of thousands of contributors have submitted millions of fungal observations on CS
456    platforms. These represent a variety of data types including primary and secondary image
457    data, location data, sequence data, and a variety of metadata formats ranging from
458    qualitative text-based descriptions to linked projects and confidence scores. Multiple efforts
459    are underway to maximize the utility of this influx of information and link diverse data types
460    across platforms for informative use and reuse. Managing data quality at this scale is
461    another point of concern, because participant experience, community feedback, and curation
462    vary widely. Beyond platforms designed for CS participation, numerous web-based
463    applications curate fungal observations presently largely untapped for research. For
464    example, the Facebook Group "Mushroom Identification" has 359,709 members who have
465    posted over 1 million photos as of 28 June 2023.
466
467    Data should be openly accessible and presented in a widely-usable format. Mechanisms for
468    the procurement of flat files are available on most major platforms (e.g., via the 'Get Data'
469    filters built into GBIF, which can further link downloaded observation lists with a DOI for
470    research publications). Many such platforms include options to include multiple data types
471    directly, along with options to cross-list data housed on different platforms. For example,
472    iNaturalist.org also includes fields for barcode sequences and vouchering information that
473    can be linked to other databases (e.g., NCBI GenBank, MycoPortal) and resultant
474    publications. Even when observations lack metadata, they can be useful for a variety of
475    purposes, such as phenology and image mining through ML. Therefore, is it critical that all
476    CS projects are preserved and publicly accessible for reuse, including unprocessed raw data
477    packaged under a stable DOI in a long-term repository such as Data Dryad
478    (https://datadryad.org/) or Zenodo (https://zenodo.org/), in accordance with the FAIR data

479 principles (Lofgren & Stajich, 2021; Wilkinson et al., 2016). To increase the accessibility of
480 data posted to alternative platforms such as social media groups, we encourage group
481 moderators to promote cross-posting to CS repositories, which could also be facilitated via
482 third-party apps.
483
484 *Translating data into action*
485 The conservation of fungi lags behind that of other organismal groups (Gonçalves et al.,
486 2021; Lofgren & Stajich, 2021). Building support and understanding around fungal
487 conservation is a significant challenge that must be addressed with multiple stakeholders,
488 including the public, policy makers, governments, and funding agencies. Public campaigns
489 such as that developed by Fungi Foundation (https://www.ffungi.org) have helped build
490 appreciation for fungal conservation among the general public, but interest from policy
491 makers and funding agencies remains meager. Research funding for taxonomists is low
492 (Britz et al., 2020) and related to a dearth in academic positions in fungal taxonomy. CS
493 projects can help fill some of these funding gaps by providing community-sourced data, but
494 monetary assistance is still needed to support the scientists and institutions leading these
495 initiatives.
496
497 CS project leaders and CS databases should prioritize the collection and accessibility of data
498 necessary for Red List assessments, including range descriptions and abundance estimates
499 that include the ability to infer true absences. To translate Red List status into legal
500 protection, a species must be included in legislation. However, the manner and extent of
501 protection can vary drastically among different countries. In the US, for example, the
502 Endangered Species Act (ESA) is widely regarded as the most significant piece of policy
503 regulating species protection. As of 27 June 2023, of the 1,870 species currently considered
504 endangered under the ESA, three are lichens, and none are free-living fungi
505 (https://ecos.fws.gov/ecp/report/taxonomic-list-tess).
506
507 **5 ENGAGING CITIZEN SCIENCE**
508 Here, we present a call for professional mycologists to engage with amateur naturalists and
509 local communities to contribute knowledge of fungal diversity, distributional ranges,
510 phenology, and occurrence data to inform Red List assessments of species. Professional
511 researchers may feel uneasy about relying heavily on CS participants for their research, due
512 to concerns about data quality and metadata completeness, the added professional
513 demands created by working with amateurs, and lack of funding. While it is important to
514 strive for best practices regarding observations and fungarium collections, these should not
515 exclude much useful data and or dissuade beginners, students, and amateurs from getting
516 involved or sharing observations and collections.
517
518 Some projects are more amenable to CS participation than others. To help professional
519 mycologists decide whether their projects may benefit from CS, we have constructed a
520 dichotomous key based on the decision framework by Pocock et al. (2014):
521
522 1. Some or all aspects of project can be completed entirely online……………………………
523 ……………………………………………………………………………… **suitable for CS**
524 1'. No aspects of project can be completed online…………………………………………… (2)
525
526 2. Project involves collection of something too small to be seen with naked eye……… (3)

527 2'. Project involves collection of something visible to naked eye…………………………  (4)
528
529 3. Project leader has ability to train participants in proper sampling (e.g., with design of
530 pamphlets or videos)……………………………………………………………………  (4)
531 3' Project leader does not have ability to train participants in proper sampling………………
532 ……………………………………………………………………  not suitable for CS
533
534 4. Sites are located where people frequently go……………………………………………  (5)
535 4'. Sites are not located where people frequently go………………………………………………
536 …………………………………………………………  **suitable for CS**, if properly incentivized
537
538 5. Participants need authorized access to field sites to collect………………………………………
539 …………………………………………  **suitable for CS**, if proper permitting can be obtained
540 5'. Participants do not need authorized access to field sites to collect……………………  (6)
541
542 6. Collection or observation of samples requires complex protocols (including special
543 equipment)……………………………………………………………………  not suitable for CS
544 6'. Collection or observation of samples does not require complex protocols……………  (7)
545
546 7. Individuals require special expertise to accurately identify collections or observations
547 …………………………………………………………………………………………  (8)
548 7'. Individuals do not require special expertise to identify collections or observations
549 ………………………………………………………………………  **suitable for CS**
550
551 8. Expert volunteers are readily available to work on project………………  **suitable for CS**
552 8'. Expert volunteers are not readily available to work on project…………………………  (9)
553
554 9. Project leader has ability to invest in training……………………………  **suitable for CS**
555 9'. Project leader does not have ability to invest in training………………  not suitable for CS
556

557 **AUTHOR CONTRIBUTIONS**

580

581  **CONFLICT OF INTEREST STATEMENT**
582  The authors declare no conflict of interest.

583

584  **DATA AVAILABILITY STATEMENT**
585  No new data were collected during the writing of this paper.

586

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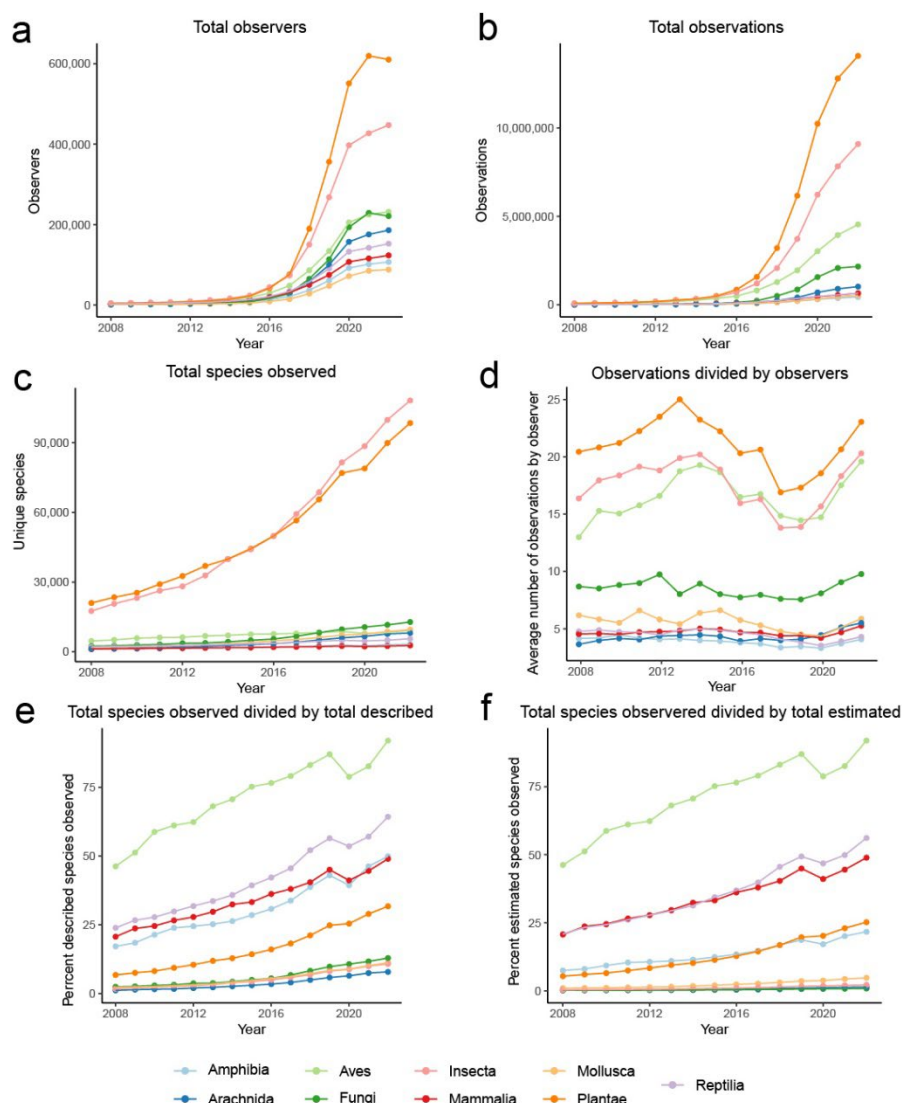847

**FIGURES**

850
851 **Figure 1.** Annual data on observations, observers, and species in nine organismal groups on
852 iNaturalist.org from 2008 to 2022. **a.** Total observers. **b.** Total observations. **c.** Total unique species
853 observed. **d.** Average number of observations by observer. **e.** Percentage of total described species
854 observed. **f.** Percentage of total estimated species observed. Total described and estimated species
855 in e and f derived from https://www.dcceew.gov.au/science-research/abrs/publications/other/numbers-
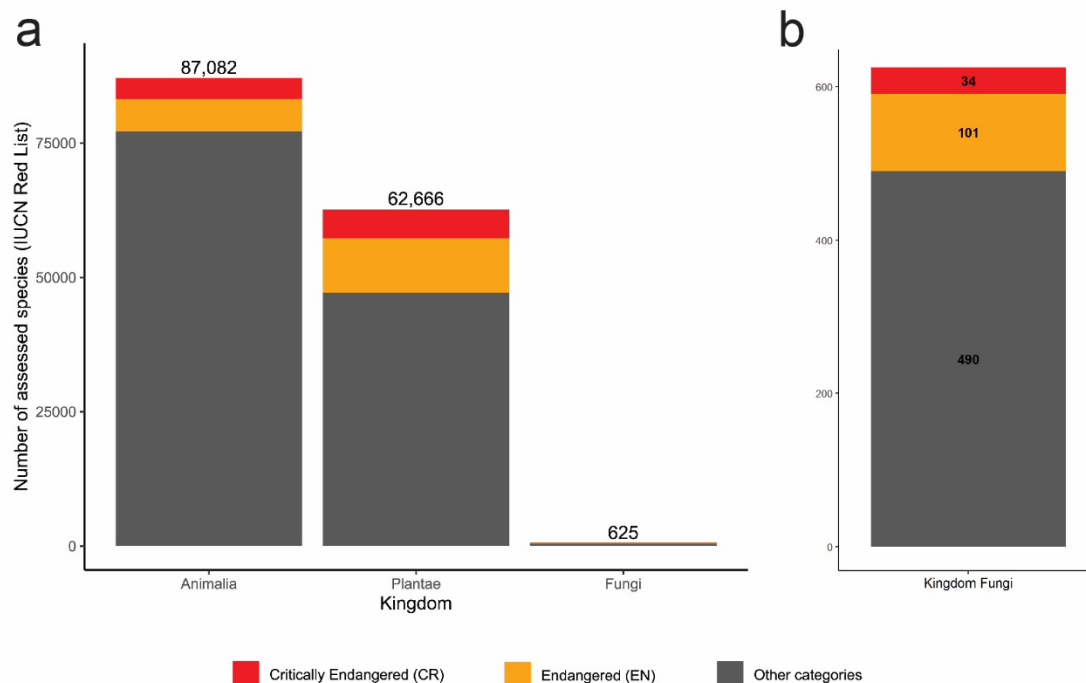856 living-species/executive-summary.
857

858
859 **Figure 2.** Number of species assessed on the IUCN Red List of Threatened Species (IUCN 2023). **a.**
860 Assessments completed for three eukaryotic kingdoms. **b.** Assessments completed for the kingdom
861 Fungi. Data taken from https://www.iucnredlist.org/resources/summary-statistics.