

Toward Reliable Biodiversity Dataset References

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Abstract

No systematic approach has yet been adopted to reliably reference and provide access to digital biodiversity datasets. Based on accumulated evidence, we argue that location-based identifiers such as URLs are not sufficient to ensure long-term data access. We introduce a method that uses dedicated data observatories to evaluate long-term URL reliability.

From March 2019 through May 2020, we took periodic inventories of the data provided to major biodiversity aggregators, including GBIF, iDigBio, DataONE, and BHL by accessing the URL-based dataset references from which the aggregators retrieve data. Over the period of observation, we found that, for the URL-based dataset references available in each of the aggregators’ data provider registries, 5% to 70% of URLs were intermittently or consistently unresponsive, 0% to 66% produced unstable content, and 20% to 75% became either unresponsive or unstable.

We propose the use of cryptographic hashing to generate content-based identifiers that can reliably reference datasets. We show that content-based identifiers facilitate decentralized archival and reliable distribution of biodiversity datasets to enable long-term accessibility of the referenced datasets.

Keywords— Biodiversity, Ecological Informatics, Information Systems, Information Retrieval

Introduction

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Over the course of hundreds of years, naturalists and biologists have
systematically collected physical evidence from an ever-changing natural
world. Through well-established protocols and institutional support, many
of these natural history collections have withstood the ravages of time
(Davis and Schmidt 1996, Hortal et al. 2015). Records that describe these
carefully collected specimens are now made available digitally through
online search indices, registries, and data archives (Page et al. 2015). The
increased availability of digital natural history records helps realize Charles
Elton’s vision of “[linking] up into some complete scheme the colossal store
of facts about natural history which has accumulated up to date in this
rather haphazard manner” (Elton 1927). So far, various initiatives have
succeeded in providing comprehensive aggregate views from previously
scattered natural history record siloes (Edwards 2000, GBIF 2019,
Matsunaga et al. 2013, Michener et al. 2011, Rinaldo and Norton 2009).
However, we show that these aggregate views are subject to change as
their underlying digital source data changes or becomes inaccessible.
Although efforts have been made to track changes in datasets with
versioning, last-modified dates (Robertson et al. 2014, Wieczorek et al.
2012), and periodic archiving (Costello et al. 2013), no systematic
approach has been adopted to keep our digital natural history record
accessible. Despite centuries of expertise in preserving our physical natural
history records, biologists currently struggle to maintain a growing body of
digital data that can change or disappear with the push of a button.

Our scholarly record consists of an intricate web of associations between
scientific studies and the datasets on which they are based. These

associations are made explicit through citations that can be used to
reconstruct a study’s context and provide the chain of evidence that
supports its claims (Garfield et al. 1964). In the pre-Internet era, the
lookup of cited references required access to one or more of the many
academic libraries in the world. With the rise of Internet-accessible
scientific publications, authors and readers access these references by using
a networked device to download content from publication websites. This
means that researchers are increasingly citing online works to support their
claims. Because the citation format of online works typically documents
only when (e.g., 2019-10-01) and where (e.g., <https://doi.org/10.123/456>)
the referenced work was accessed by the author (DataONE 2012, GBIF
2019, iDigBio 2016), the reader expects the web-accessed resource to
remain accessible and unaltered via this single web location. Readers may
attempt to find a version of the works referenced by searching online data
repositories for the matching author and title, but there is no guarantee
that information found this way will be exactly the same as what was
originally referenced. Any reference that does not allow readers to find the
referenced work fails to satisfy the first FAIR principle of findability: “F1.
(meta)data are assigned a globally unique and eternally persistent
identifier” (Wilkinson et al. 2016). Our study supports Klein’s and
Vision’s findings that networked, location-based access to digital objects is
an unreliable mechanism for providing continued access to the unaltered
original work (Klein et al. 2014, Vision 2010). Unless we change the way
we preserve and cite our digital scholarly works, the web of knowledge that
forms the basis of our scientific record will degrade.

Problem Characterization

The current practice of using Uniform Resource Locators (URLs) (Berners-Lee et al. 1994) to reference online biodiversity datasets provides no guarantee of continued data accessibility. This uncertainty jeopardizes the integrity of the scholarly record. When data access is lost, documented research results may become impossible to reproduce and the justification for conclusions or hypotheses that rely on lost results may be undermined.

Biodiversity data aggregators, such as DataONE, GBIF, and iDigBio, rely on data providers such as data curators and institutional repositories to maintain active dataset URLs, and aggregate the data found at those URLs for distribution in response to user queries. From here on, we use the term “data network” to refer to a collection of URLs that are discoverable through some central URL registry, and the term “provider network” to refer to the subset of URLs in a biodiversity aggregator’s data network from which the aggregator retrieves data.

Relying on URLs to locate and identify referenced data carries the risk of link rot and content drift (Klein et al. 2014). Link rot occurs when a URL, or link, that had previously responded to queries can no longer be reached. This can happen, for example, due to temporary outages, URL retirement, or URL migration. A link exhibits content drift when a query to the link provides content that is different from the content it provided in the past. The extent of content drift can vary; content may have received only minor edits with no changes in semantics, or it may reference a different entity altogether. When a single URL is used to locate data that may change over time, a particular data version may become inaccessible over time. In one study on the *Genetics* journal, it was

reported that 40% of links (URLs) to supplemental materials became
unavailable due to link rot within one year of publication (Vision 2010).
Another study (Klein et al. 2014) confirmed that as many as one in five
Science, Technology, and Medicine articles contained references that
exhibit “reference rot,” which includes either link rot or content drift.

In this paper, we propose a methodology for measuring the existence of
link rot and content drift in online data networks, then provide
experimental results that confirm the existence of link rot and content drift
in the provider networks of BHL, DataONE, iDigBio, and GBIF. Finally,
we propose a method for referencing and serving biodiversity data in a way
that works toward satisfying the Findable, Accessible, Interoperable, and
Reusable (FAIR) principles (Wilkinson et al. 2016).

Methodology

While previous studies focus more generally on reference rot of URLs cited
in scientific works (Klein et al. 2014, Vision 2010), our study provides
quantitative evidence that reference rot occurs in biodiversity provider
networks. Because reference rot occurs in the scope of individual data
references, and references to digital datasets rely on URLs to locate the
data, we begin by introducing terminology for characterizing the reliability
of a URL according to how often it exhibits link rot and content drift.

URL Reliability

We assume that the URLs used to reference biodiversity datasets are
expected to resolve to an Internet Protocol (IP) (Postel 1981) address via

the Domain Name System (Mockapetris 1987). If a web server is accessible 124
at the resolved IP address, a query (i.e., HTTP get request) to that 125
address over the Hypertext Transfer Protocol (HTTP) will return a 126
response code and, in some cases, associated content (Berners-Lee et al. 127
2005). We classify the reliability of a URL according to the content, or lack 128
of content, that it provides over successive queries. If a query to a URL is 129
unsuccessful, we say that link rot has occurred. However, if a successful 130
response is received but the retrieved content is different from the content 131
retrieved by previous query, we say that content drift has occurred. 132
Monitoring URLs in this way allows us not only to determine whether link 133
rot and content drift occur, but also to capture their long-term behaviors. 134
For example, one URL that has exhibited link rot might have failed to 135
respond only once, whereas another might have become consistently 136
unresponsive. Likewise, one URL might exhibit content drift less frequently 137
than another whose contents change rapidly. Furthermore, various 138
combinations of link rot and content drift behavior may indicate that one 139
URL is more reliable than another, even though both exhibit reference rot. 140

We label URLs with sets of reliability indicators according to their link 141
rot and content drift behaviors. The defined reliability indicators are 142
differentiated by the degree of link rot and content drift observed over a 143
series of queries to the URL at different points in time. We characterize 144
the responsiveness of a URL according to whether it exhibits link rot: 145

- Unresponsive: the link has failed to respond to one or more queries 146
- Responsive: the link has responded to all recorded queries 147

We characterize the stability of a URL according to whether it produces 148
different content from one query to the next: 149

• Unstable: the content that the link points to sometimes changes	150
• Stable: the content that the link points to never changes	151
We characterize the overall reliability of a URL according to both its	152
responsiveness and stability:	153
• Unreliable: the link does not always provide the expected content; it	154
is either unresponsive, unstable, or both	155
• Reliable: the link always provides the expected content; it is both	156
responsive and stable	157
In order to determine the reliability of any given URL over time, we	158
must monitor its behavior by documenting how it responds to periodic	159
queries. We propose a method for monitoring URL behavior in the Data	160
Collection Over Time section of this paper. First, however, we must	161
propose a method for documenting a URL's response to a single query. For	162
the context of biodiversity, we consider the case in which any content that	163
a URL produces is a dataset.	164

The Data Collection Process 165

We suggest that digital dataset collection practices have some analogies to 166
well-established physical specimen collection procedures (see figure 1) 167
(Poelen 2019d). If datasets are considered analogous to specimens, then 168
the URLs that locate datasets on the Internet are analogous to the 169
physical locations of specimens in the natural world; they are where digital 170
datasets were originally found, but not where they should be preserved. 171
Once found, physical specimens are collected by hand; similarly, digital 172

datasets are downloaded by querying their URLs. Once a specimen is collected and deposited to a safe, accessible repository, a record is kept that documents what the specimen is in addition to when, where, and by whom it was collected.

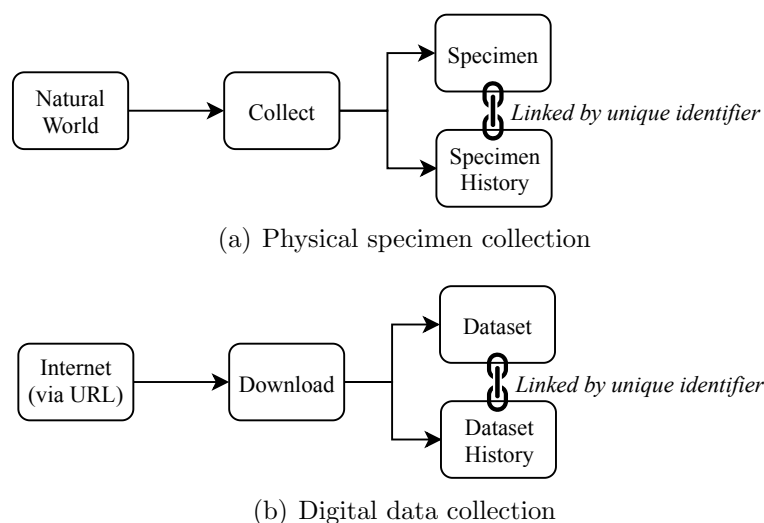


Figure 1. Reliable record keeping for digital datasets (b) can be achieved in an analogous way to current practices in record keeping for physical specimens (a). Biologists collect physical specimens from the natural world, thoroughly document the process, then store the specimens in facilities equipped for long-term preservation. Analogously, digital datasets that are downloaded from the internet can be thoroughly documented and archived in dedicated repositories for long-term preservation. Just as the collection of physical specimens is recorded and identified in specimen information records, the downloading of digital datasets can also be recorded and identified in dataset provenance records.

The same can be done for downloaded datasets. When a dataset is downloaded, a record can be kept that details the URL that was queried, the time of query, and who (e.g., a human or software agent) issued the

query that initiated the download event; we refer to this record as the
dataset’s provenance record (Pasquier et al. 2017). Additionally, the
dataset itself should be stored in a safe, accessible dataset archive so that
it may be retrieved at a later date if needed. The final step in the
collection process is to link the preserved specimen to its corresponding
record (see figure 1(a)) via an assigned unique identifier.

The identifiers assigned to datasets must differ only if the contents of
their datasets differ. This can be achieved by deriving the identifiers from
the contents of their datasets. Furthermore, the identifier must be unique
to the dataset; a dataset will always be assigned the same identifier and no
two datasets (including different versions of a dataset) can share an
identifier. Cryptographic hashing is one such method for producing
content-based identifiers which are both content-derived and unique. A
variety of cryptographic hashing algorithms exist that receive some digital
file as input and uniquely encode its contents into a fixed-length series of
bits called a “hash.” We use hashes generated by the SHA-256 algorithm
(NIST 2001) as unique content-based identifiers. For example, given two
different bits of text, “first example” and “second example”, their
computed SHA-256 hashes (in hexadecimal format) are b84283f1f4cb997eae
b28dce84466678ea611824ac97978749b158d2cd3886ac and c64eee387ccc1d04
38765129a8c423dab0b67d094710e395ac3193c52591a3ba, respectively. These
hashes are the only ones that can possibly be computed from the example
texts using the SHA-256 algorithm, and no other input to the SHA-256
algorithm can produce either of these specific hashes (NIST 2013). One
benefit of the SHA-256 algorithm is that its computation time and space
requirements scale linearly and remain constant, respectively, with the

amount of data being hashed (NIST 2001). That is, computing a hash for 206
a dataset that is twice as big as another dataset should take twice as long 207
but use the same amount of memory. This is important for the biodiversity 208
domain, where large media files such as computed tomography (CT) scans 209
may consist of terabytes of data (Keklikoglou et al. 2019). Another benefit 210
is that all SHA-256 hashes have the same length, regardless of the amount 211
of data being hashed; a hash computed for a terabyte-sized CT scan is no 212
longer than the hash computed for “first example”. 213

Content-based identifiers that meet the requirements we have described 214
are reliable references; they are not susceptible to either link rot or content 215
drift. Additionally, the derivation of the content-based identifier for a 216
given dataset can be performed by anyone, anywhere, and at any time. 217
There is no need for some central authority to generate and assign 218
identifiers, as is the case for non-content-based identification schemes 219
(Paskin 1999). Therefore, dataset provenance can be collected in a 220
decentralized manner; if two agents collect provenance for the same dataset 221
acquired from potentially different locations, they can both reference the 222
dataset using the same content-based identifier without any need for 223
coordination. In this scenario, the two provenance records produced by the 224
two agents can also be uniquely identified by using content-based 225
identifiers in the same manner as we identify and reference datasets. We 226
elaborate on uses for identifying and referencing provenance records in the 227
discussion section of this paper. 228

Data Collection Over Time

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By establishing a dedicated data observatory, we can build a history for
each observed URL to capture its reliability over time. Such an observatory
periodically queries URLs in a data network and produces for each URL
two complementary parts: 1) an archived copy of the response to the
corresponding query, whether it was a dataset, an error code, or no reply at
all, and 2) a record of its provenance, including the URL itself, the current
date, and a content-based identifier of any dataset received. Successive
provenance records can be aggregated to construct comprehensive histories
for both datasets (when and where they were found) and URLs (which
datasets they located over a series of queries over time).

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The constructed URL histories can be analyzed to determine whether a
link was ever broken, when it was broken, and whether it became
responsive again. The logs also identify the content (or lack of content)
that a URL located each time it was queried. Any change in the content
identifier from one query to the next indicates a change in the content of
the dataset. These link breakages and content changes correlate to link rot
and content drift, respectively, and allow us to determine the
responsiveness, stability, and reliability of each URL over time.

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URL Reliability in Data Networks

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Our method for monitoring the behavior of a single URL over time can be
applied to monitor all URLs in a data network. We also extend the idea of
URL reliability to data networks and propose that the overall reliability of
a set of URLs in a data network can be evaluated by monitoring the
reliability of each URL over time. First, we label individual URLs with

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binary indicators of responsiveness, stability, and reliability at each time 254
they were queried. Next, we characterize data networks according to the 255
percentages of URLs that are assigned each of the reliability indicators. 256
For example, if a data network contains three distinct URLs and we find 257
that only two out of the three are reliable, then we say 67% of the URLs in 258
the data network are reliable. 259

Experiment 260

The Preston biodiversity dataset tracker (Poelen et al. 2018) implements 261
mechanisms for monitoring URLs in provider networks. It allows users to 262
deploy a data observatory that discovers URLs in the provider network of 263
a biodiversity aggregator, queries each URL for data, documents the data 264
collection process, then archives the results. All crawl activities, the 265
queries they issue, and the results they produce are recorded in a string of 266
provenance logs. It is important to note that the URLs in provider 267
networks are the sources of the datasets ingested by aggregators, not 268
necessarily the datasets served by the aggregators, which may have been 269
altered to, for example, to add alternate taxonomic information ([GBIF] 270
Global Biodiversity Information Facility 2019b). 271

We deployed several Preston observatories to monitor the provider 272
network URLs registered in Biodiversity Heritage Library (BHL), Data 273
Observation Network for Earth (DataONE), Global Biodiversity 274
Information Facility (GBIF), and Integrated Digitized Biocollections 275
(iDigBio). The provider network URLs for DataONE, GBIF, and iDigBio 276
were queried monthly from March 2019 through May 2020. The BHL 277
provider network was queried monthly from May 2019 through May 2020. 278

The logs taken by each of these observatories describe the URL queries and their results, which were processed to produce the results that follow. To analyze the full set of URLs observed across all four provider networks, an fifth observatory was constructed by aggregating the provenance records produced by the four provider network observatories. In an effort to minimize artificial link rot due to Internet access issues in our local network, we deployed the Preston observatories in a large commercial data center in Germany.

Results

Breakdowns of the overall reliabilities of the sets of URLs observed within the provider networks are provided in table 1. Results are listed as percentages and total counts of URLs in the provider network that were assigned each reliability indicator. When analyzing the recorded results of queries to URLs in each provider network, we found that, for each individual network, 5% to 70% of registered URLs were intermittently or consistently unresponsive, 0% to 66% produced unstable content, and 20% to 75% became either unresponsive or unstable over the period of observation.

We found that 43% of URLs observed across the four provider networks became unreliable at some point over the period of observation. Of those unreliable URLs, 41% were unstable, 11% became consistently unresponsive, and 71% were at best only intermittently responsive. For 5% of successful queries, the URL failed to respond to the next query. For 4% of successful queries, the URL provided different content in response to the next successful query.

Provider Network	Responsive URLs	Stable URLs*	Reliable URLs
BHL ^a	29.99% (77,040)	99.95% (241,243)	29.97% (76,998)
DataONE ^b	92.54% (394,568)	87.11% (367,957)	80.30% (342,363)
GBIF ^c	73.93% (60,564)	33.93% (22,491)	24.53% (20,093)
iDigBio ^c	86.80% (5,988)	61.99% (4,265)	54.41% (3,754)
All observed URLs**	69.62% (534,107)	86.46% (632,879)	57.43% (440,606)

Table 1. Overall responsiveness, stability, and reliability for URLs observed in each aggregator’s provider network and for all observed provider network URLs as of May 2020. Numbers in brackets indicate total URL counts. *URLs that never provided content were omitted from the denominator when calculating Stable URLs percentages. **Because URLs may be registered in more than one provider network, the total number of observed URLs is expected to be less than the sum of the URL counts for each network. ^{a?}
^{b?} ^{c?}

The changes in reliability over time for each provider network are visualized in figure 2. Note that because we have defined reliable URLs to be those considered both responsive and stable, they always represent the smallest fraction of URLs in table 1, figure 2, and figure 3. Figure 3 visualizes the cumulative growth of biodiversity provider networks during their periods of observation. This growth is illustrated with two metrics: the cumulative total number of unique URLs observed in each network and the cumulative total number of unique contents that were downloaded from the network at each monthly sampling.

The behaviors of the distributions over time of responsive, stable, and reliable URLs vary notably between provider networks. Reasons for these differences might be inferred when cross-examining table 1 and figures 2 and 3. For example, although the set of URLs observed in the BHL provider network scored relatively low in responsiveness due to frequent

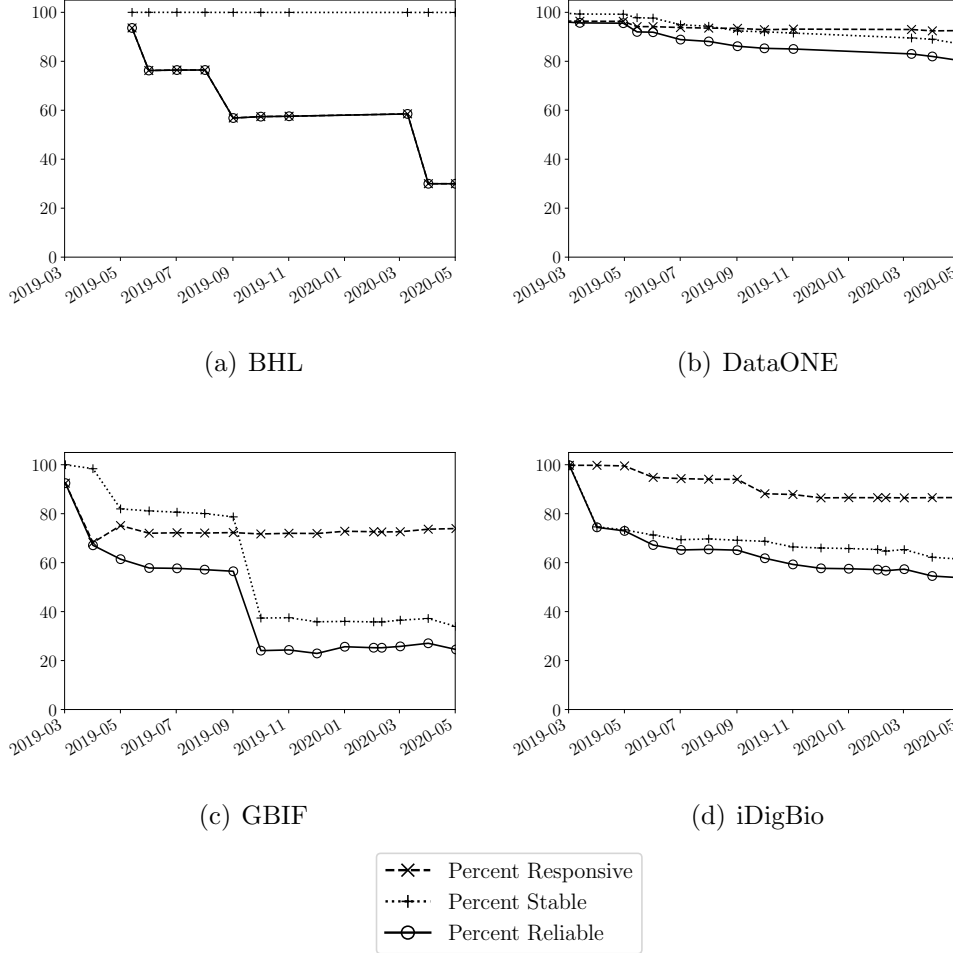
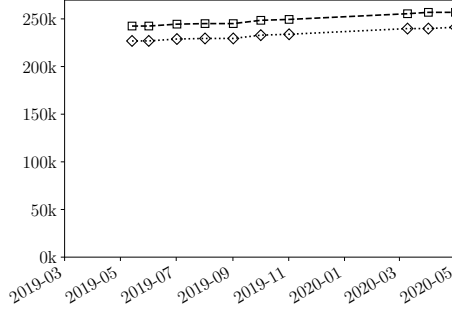
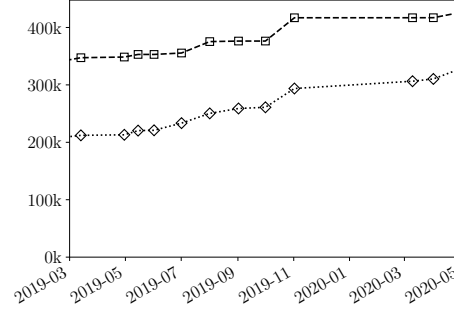


Figure 2. Overall responsiveness, stability, and reliability from March 2019 through May 2020 as percentages of URLs that exhibit each indicator in the provider networks of (a) BHL, (b) DataONE, (c) GBIF, and (d) iDigBio.

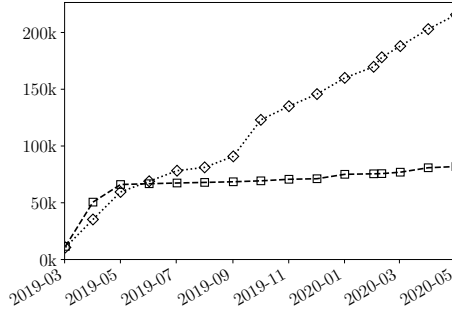
link rot, they were more stable than the provider network URLs of other 318
aggregators because content drift within the BHL provider network is 319
relatively rare. Conversely, although URLs observed in the iDigBio 320
provider network were relatively responsive, they scored low in stability 321
because the network’s near-constant content growth far outpaces its URL 322



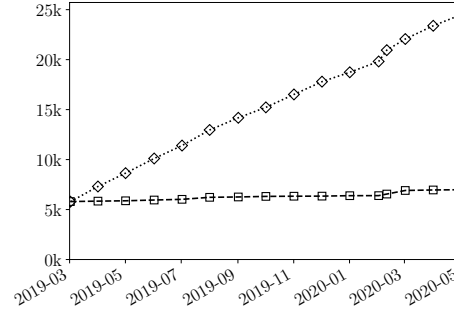
(a) BHL



(b) DataONE



(c) GBIF



(d) iDigBio



Figure 3. Total number of URLs and unique contents observed from March 2019 through May 2020 in the provider networks of (a) BHL, (b) DataONE, (c) GBIF, and (d) iDigBio.

growth. The behavior of the GBIF provider network was characterized by 323
large sporadic swings; a mass URL migration of over 14,000 Plazi-hosted 324
datasets occurred in May, introducing thousands of new URLs over a short 325
period of time, while over 31,000 URLs (60% of URLs that responded to 326
queries that month) suddenly changed contents in October 2019. Even the 327
most reliable set of URLs, observed in the DataONE provider network, 328
shows a clear downward trend in all three categories, with 13% of URLs 329

becoming unreliable over a period of fourteen months. Additionally, the
DataONE provider network’s growth curves indicate that there are far
fewer unique contents than unique URLs. This mismatch suggests two
possibilities: either much of the provider network’s URL population is
unresponsive, or DataONE lists multiple provider URLs for many of its
datasets. Because the DataONE provider network has been shown to be
highly responsive, it could be the case that many distinct URLs refer to
the same datasets. It’s also worth noting that the June and September
spikes in BHL’s unresponsiveness were largely due to URLs that failed to
respond in those particular months but did respond to future queries.

Sources of Potential Numerical Error

We expect that the URL reliability counts generated for the figures and
tables are lower than their actual values. When we qualified URLs as
being reliable, responsive, and stable, we could not be certain that links
did not briefly become unresponsive or change content during the
month-long periods between queries. It is therefore likely that some cases
of link rot and content drift were not reflected in the results. Additionally,
we only queried provider network URLs that the aggregators list in their
dataset URL registries; this means that, if a URL were removed from an
aggregator’s registry, we would not be able to detect subsequent instances
of reference rot. Therefore, our results represent an optimistic upper
bound on provider network URL reliabilities.

The results for the DataONE and GBIF provider networks in figure 2
are sometimes skewed due to Preston’s interactions with the pagination
method that the aggregators use to supply users with their dataset

registries. Registry pages contained set amounts (e.g., 20) of URLs and
represent small slices of the registry. For registries that use pagination, the
observatory would keep querying for registry pages until reaching the page
or failing to get a response. For instance, GBIF’s URL and dataset totals
in March 2019 (see figure 3(c)) are low because an early query to a GBIF
registry page was not answered and, consequently, the URLs of registry
pages that should have followed were not discovered. Similar events
happened for both the GBIF and DataONE observatories at later points in
time, potentially overestimating the reliability of the URLs in their
provider networks.

For the iDigBio provider network, an issue with Preston’s parsing of the
iDigBio URL registry prevented the discovery and querying of a subset of
URLs before February 2020, when the issue was detected and fixed. This
likely accounts for the surge in the total number of contents and URLs in
early February 2020.

The observatories for DataONE and BHL failed to save new provenance
records for December 2019 through February 2020 due to a technical error
on their shared server. Therefore, no new contents or URLs were reported
for the provider networks of these aggregators during this time frame.

Discussion

We note that our experiment did not consider datasets other than those in
the provider networks, i.e., those referenced in the aggregators’ registries of
data providers. For example, datasets that are retrieved from iDigBio or
GBIF via portal/API queries or download events were not included. These
datasets also have URL-based references and, unlike provider datasets, are

hosted by the aggregators. These URLs are used to reference biodiversity
datasets according to existing biodiversity network citation guidelines
(DataONE 2012, GBIF 2019, iDigBio 2016). However, while we do not
have quantitative measurements of stability for these URLs, content drift
can take place. This is because datasets correspond to specific queries
which over time produce different content depending on the changes in the
data aggregated from the providers. Similarly, link rot can happen when
the aggregator systems are down or storage limitations dictate the deletion
of datasets. The architecture and policies used for storing and referencing
these datasets differ among aggregators and are outside the scope of this
paper.

We have shown that the reliability of URLs decreases over time in all of
the provider networks that we monitored. If current trends continue, their
reliabilities will continue to worsen. Systematic changes in the way we
preserve and reference data are needed to improve the longevity and
long-term integrity of the biodiversity data record. Before we propose such
changes, it's necessary to first understand why URLs are proving to be
ill-suited for referencing data in the long term.

Unreliability of Location-Based Identifiers

The problems related to using URLs for referencing datasets are largely
due to the fact that they are location-based identifiers: they describe
where the data is but not necessarily what it is. Also, by definition, data
accessed via URLs must be mediated by a central authority, such as the
institutional repositories that serve biodiversity datasets, who can match
location-based identifiers with data. Interested users are expected to trust

the central authority to guarantee long-term access to the referenced data 405
in its original form. 406

The use of URLs as identifiers violates the requirements of uniqueness 407
and persistence (Paskin 1999). An identifier must only ever identify one 408
entity (uniqueness) and must persist longer than the entity it identifies 409
(persistence) (Paskin 1999). However, as we have shown in our 410
experiments, many URLs do not possess both uniqueness and persistence; 411
unstable URLs forfeit uniqueness in the event of content drift, while 412
unresponsive URLs do not persist as long as the datasets they identify. 413

At the core of URL instability is the current practice of using URLs to 414
identify evolving datasets rather than using content-based identifiers to 415
identify fixed dataset versions. If biodiversity data providers were 416
uniformly committed to allocating one URL per dataset version, then 417
content drift might become less common, improving overall URL stability; 418
however, widespread social adoption of such a commitment from all data 419
providers may be unrealistic. Additionally, such a commitment would not 420
address link rot and URL unresponsiveness. Even if a similar commitment 421
were made by data providers to guarantee the long-term responsiveness of 422
URLs, it could not address the case where a data provider either loses 423
authority over a domain name or migrates to another. For example, our 424
deployed Preston observatories recorded the sudden migration of over 425
14,000 Plazi datasets from the <http://plazi.cs.umb.edu/> domain to 426
<http://tb.plazi.org/>, an event which invalidated any references to URLs 427
within the first domain. 428

The instability that we have observed across the URLs in provider 429
networks is to be expected, and is not a measure of the quality of either 430

the provider networks or their aggregators. In fact, regular updates to
datasets (i.e., URL instability) might indicate continued growth,
maintenance, and refinement of those datasets. One might even argue that
a stable dataset URL would indicate that the dataset is no longer being
maintained or is potentially outdated. Therefore, the issues resulting from
the use of URLs as references are not due to poor management on the part
of data aggregators or curators, but rather due to the fact that URLs are
inherently unreliable.

Paskin proposed that “the best way to ‘future proof’ an identifier
scheme is to forego any intelligence within the identifier itself” (Paskin
1999), where the notion of intelligence refers to the inclusion of meaningful
information in the textual representation of the identifier. URLs are
typically structured according to the Domain Name System specification
(though URLs may include an IP address instead of a domain name) and
inherently contain some minimum amount of intelligence, namely the
domain to which the URL belongs (Mockapetris 1987). Thus, it is
necessary to look to another identification scheme to allow for proper
identification and reliable referencing.

An Alternative: Unique Content-Based Identifiers

Instead of identifying digital datasets by location (e.g., a URL), we can
identify datasets by their content. One way to achieve this is to use
algorithmically generated content-based identifiers. A variety of
cryptographic hashing algorithms are available that guarantee a unique
hash, representable as text, for any given dataset (NIST 2001). Because
the hash is deterministically derived from the content it identifies, we say

that it is a content-based identifier. These content-based identifiers can be
generated for a dataset using openly available algorithms, without a
mediating central authority (Paskin 1999). If a change is made to the
dataset, then the hash computed from the modified dataset will be
different from that of the original. Therefore, if the hash of a dataset is the
same as the referenced hash, it must be the originally referenced dataset
(figure 4(c)) (NIST 2001). Using hash identifiers eliminates the possibility
of content drift.

The shift from location-based to content-based identifiers decouples
future dataset accessibility from the original point of access. As long as
there exists some discoverable and accessible data repository that serves
the desired content, that content can always be retrieved. Such data
repositories can be made discoverable through content hash registries such
as hash-archive.org (Trask 2015). In response to a user query for a content
hash, these content hash registries would provide a list of locators (e.g.,
URLs), if any, that direct users to the referenced data (e.g., a registry
would provide URLs that retrieve data when queried). Even if one
repository becomes inaccessible due to either a temporary outage or
permanent retirement, another may be available to provide the referenced
data. When several repositories serve referenced datasets, there is no single
point of failure for content hash lookups; if a referenced dataset is
redundantly located across and within data repositories, access to the
dataset will only be lost if all associated locations exhibit link rot. Even if
access to a dataset is lost, it can be restored as long as the referenced
dataset still exists somewhere and can be made discoverable and accessible.

If a dataset version were identified with a content-based hash, its

duplication across different platforms would not lead to ambiguous
references, but rather to distributed copies of the same reliably addressed
content.

Transitioning to Reliable References

Although we propose a change in the fundamental mechanisms used to
reference datasets, existing references can be made reliable with only minor
modifications. Consider the following citation generated by GBIF
according to their citation guidelines (GBIF 2019):

Levatich T, Padilla F (2017). EOD - eBird Observation
Dataset. Cornell Lab of Ornithology. Occurrence dataset
<https://doi.org/10.15468/aomfnb> accessed via GBIF.org on
2018-09-02.

The citation references the eBird dataset hosted at gbif.org as it was
retrieved on September 2, 2018. However, at the time of writing, the URL
<https://doi.org/10.15468/aomfnb> redirects to a GBIF internal reference
page that states the eBird dataset was last updated in March of 2019. The
dataset made available through the listed URL is different from what was
originally referenced in the citation, but it is impossible to determine the
extent of the changes without having access to previous versions of the
data.

Fortunately, references like the example above can be made more
reliable by augmenting them with a content-based identifier for the dataset.
Consider the following enriched citation for the eBird dataset that adds a
SHA-256 content hash (NIST 2001):

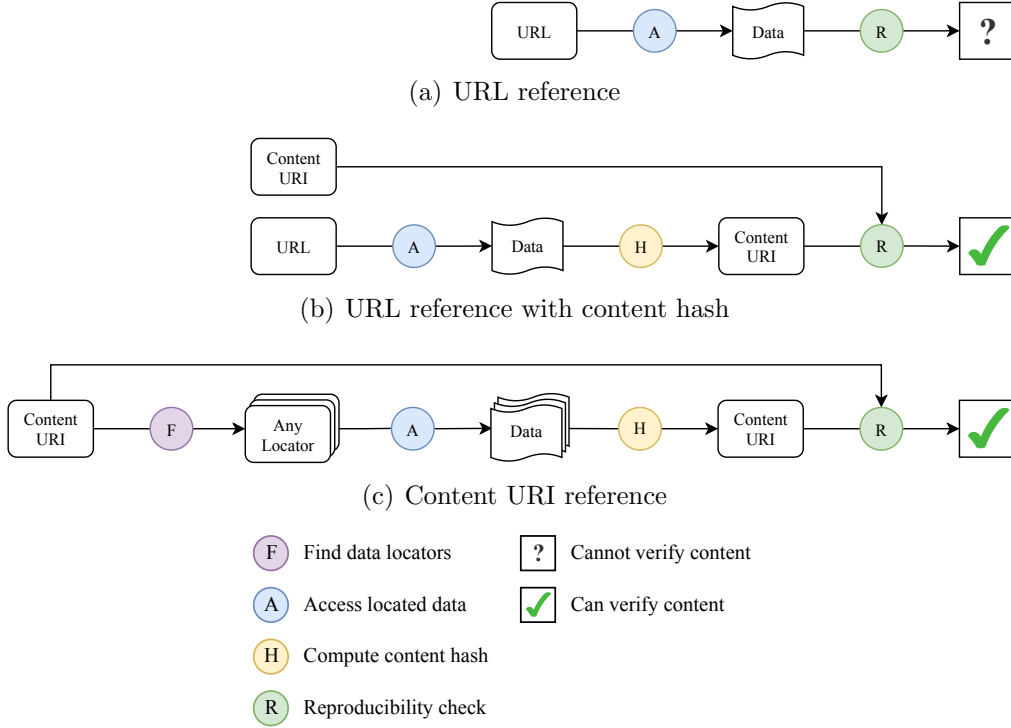


Figure 4. Content resolution and verification for references that use location- versus content-based identifiers. (a) Location-based identifiers (e.g. URLs) cannot verify the authenticity of retrieved content and are vulnerable to link rot due to the use of a fixed locator. (b) If the content hash of the referenced data is known, the authenticity of retrieved data can be verified by comparing the hash of the retrieved data with the provided content hash. However, the fixed locator is still vulnerable to link rot. (c) Content-based identifiers (e.g. Content URIs) can be used to find several locators for the referenced data and contain a content hash to verify the authenticity of retrieved data. The decoupling of the reference from a fixed locator makes the reference resistant to link rot.

Levatich T, Padilla F (2017). EOD - eBird Observation
Dataset. Cornell Lab of Ornithology. Occurrence dataset hash:
//sha256/29d30b566f924355a383b13cd48c3aa239d42cba0a55f4
ccfc2930289b88b43c accessed at
<https://doi.org/10.15468/aomfmb> via GBIF.org on 2018-09-02.

The content hash is captured in a content address Uniform Resource
Identifier (URI) (Berners-Lee et al. 2005) in the form of
hash://algo/hash-string proposed by (Trask 2015), where “algo” is a
hashing algorithm (e.g., “sha256”) and “hash-string” is the content hash
generated by the algorithm in hexadecimal format. In the example above,
the hashing algorithm is SHA256 and the hash string starts with “29d3.”
The added content hash was derived from and uniquely identifies the exact
version of the eBird dataset that was originally referenced. If an interested
user knows of and has access to an information retrieval system that has
indexed the dataset, finding the desired dataset is as simple as querying for
its content hash. With the addition of a content hash, the URL becomes
superfluous and is included merely to demonstrate that the URL and
content hash are not mutually exclusive (see figure 4(b)).

Other cryptographic hashing algorithms besides SHA-256 can be used
to generate content-based identifiers with the same uniqueness guarantees
(NIST 2013). However, note that different hashing algorithms will generate
different content hashes from the same data. We use a URI rather than
the content hash itself because it allows us to specify the hashing
algorithm. If the hashing algorithm is not specified, one might mistakenly
conclude that a dataset does not match a reference if the wrong hashing
algorithm is used to verify the dataset’s authenticity. Our proposal to use

Trask’s content-addressed URIs to reliably reference data is inspired by 532
Kuhn & Dumontier’s method to make digital content verifiable and 533
permanent using Trusty URIs (Kuhn and Dumontier 2015). We chose to 534
use Trask’s content hash URIs because they are location- and 535
content-agnostic and easy to read. However, we recognize that Trusty 536
URIs can help facilitate content retrieval and processing using a 537
location-based URI prefix and an (optional) extension suffix. 538

Other content-based identification schemes exist that resist changes in 539
format in digital content. For example, the universal numeric fingerprint 540
(UNF) (Altman and King 2007) resists such changes by first processing the 541
input data before generating a content hash. Among other preprocessing 542
techniques used when generating UNFs, numerical data may be rounded to 543
a certain precision before generating a content hash, with the 544
understanding that a dataset may undergo such format changes when 545
translated, for example, between different computing environments or 546
hardware configurations. Indeed, on manual examination of the changes 547
between successive versions of the biodiversity datasets we observed, we 548
found some cases in which two versions of a dataset (determined to be 549
different because they resulted in different content hashes) differed only in 550
formatting, such as the amount of whitespace and the sequential ordering 551
of observational records. However, for biodiversity data, we expect that 552
such format-specific content-based identification schemes would only prove 553
detrimental in practice. Standard cryptographic hashing algorithms, such 554
as SHA-256, are included in most modern software environments and enjoy 555
widespread use across different digital applications, whereas non-standard 556
algorithms, such as UNF, would first need to be installed and may be 557

unknown to most users, presenting a hurdle to their widespread adoption. 558
 Additionally, it may be unrealistic to expect preprocessing efforts to filter 559
 out non-informative data effectively enough to be able to trust that 560
 semantically identical datasets will always result in the same content-based 561
 identifiers. This is especially relevant to biodiversity datasets because they 562
 consist mostly of text data, which may be altered in a number of ways 563
 without changing the content’s meaning. 564

Enhancing Dataset References with Provenance 565

A dataset reference can also be enhanced by pointing to the record that 566
 describes its provenance. The following citation further augments the eBird 567
 dataset reference with the content hash of an associated provenance record: 568

Levatich T, Padilla F (2017). EOD - eBird Observation 569
 Dataset. Cornell Lab of Ornithology. Occurrence dataset hash: 570
 //sha256/29d30b566f924355a383b13cd48c3aa239d42cba0a55f4 571
 ccfc2930289b88b43c accessed at 572
<https://doi.org/10.15468/aomfnb> via GBIF.org on 2018-09-04 573
 with provenance hash://sha256/b83cf099449dae3f633af618b19d 574
 05013953e7a1d7d97bc5ac01afd7bd9abe5d. 575

As was the case for the dataset, the provenance itself can be retrieved 576
 by querying an information system that has indexed the hash of the 577
 referenced provenance record. Note that the provenance hash is not 578
 strictly necessary to make a dataset reference reliable; the dataset hash 579
 alone is sufficient. However, explicitly referencing the provenance of the 580
 dataset is useful because it allows future readers to retrieve the same 581

context to which the researcher referencing the dataset had access. More
generally, the provenance describes the context of the retrieval of any type
of content (e.g., datasets, metadata, citation files, etc.). The types of
information in the provenance depend on the implementation of the data
observatory, but at a minimum include the URLs that were queried to
produce the content, the dates of the queries, the format of the content,
and the data registries that were searched to find the content.

A provenance record relates to a dataset the way that a map relates to
a location: a provenance record provides a context to understand the
origin and relations of a dataset. This provenance context may be limited
to few metadata elements related to a single dataset (e.g., web location,
data format, author, license), but can also include a comprehensive
description of a biodiversity provider network consisting of thousands of
datasets and their associations. Also, because provenance records are
datasets themselves, they can be reliably referenced and embedded in other
provenance records using their content URIs. We used such a composition
of content URIs and provenance records as part of our monitoring scheme
(Poelen et al. 2018) to track the reliability of URLs in biodiversity provider
networks over time (see table 1 and figures 2 and 3). The following
citation references the history of the entire DataONE provider network
over the period of observation by one of our Preston observatories:

Poelen JH. 2019d. A biodiversity dataset graph: DataONE.
doi:10.5281/zenodo.3483218 . hash://sha256/2b5c445f0b7b918c
14a50de36e29a32854ed55f00d8639e09f58f049b85e50e3

The use cases for including the provenance hash are many. For example,
if the provenance record of a dataset is found, it may be possible to

traverse the provenance and find newer versions of the dataset. This
 requires that the various versions of the dataset were observed by a
 provenance-generating data observatory, properly archived, then made
 publicly accessible. Provenance can also be used for attribution purposes;
 a detailed record is kept of the life of each dataset, including when and
 where it was found, as well as snapshots of aggregator URL registries,
 which may provide information such as the publisher, authors, and contact
 information for each dataset. One study found that 88% of publications
 that cite biodiversity datasets do not provide enough information to
 identify the original source of the dataset (Escribano et al. 2018). Even in
 such cases, it may be possible to determine the dataset’s publisher by
 looking up identifying information, such as the dataset’s content hash,
 URL, or DOI, in available provenance records.

Dataset Retrieval Using Hash References

The dataset and provenance hashes referenced in the example references
 above were produced by our Preston observatories, which were set up to
 monitor the four provider networks. At the time of writing, both the
 referenced dataset and its provenance are available online (Poelen
 2019a,b,c, 2020a,b,c). A query for the provenance hash in the search bar at
 hash-archive.org should direct the user to an archived repository of Preston
 observations that contains both the dataset and its provenance (see figure
 5). The dataset reference is now reliable; it is effectively immune to both
 link rot and content drift. Given that Zenodo and Internet Archive serve
 as online digital archives (Internet Archive 2020, Zenodo 2019), future
 readers can expect that the URLs registered as locations for the referenced

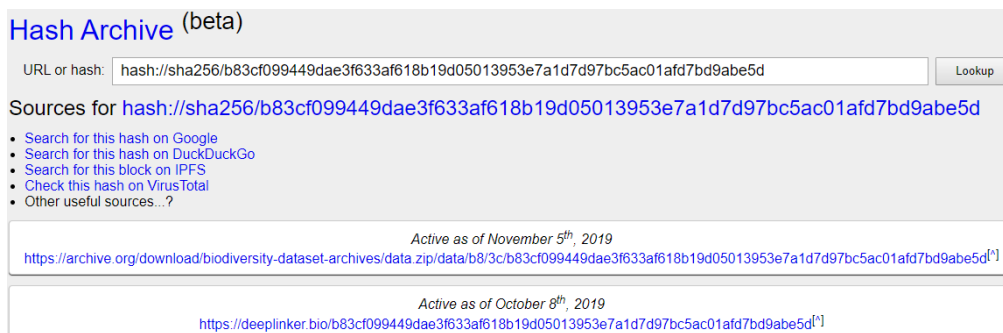


Figure 5. An example of a search index mapping hashes to archives. A search for a content or provenance hash at hash-archive.org will find any associated URLs that have been registered at hash-archive.org.

dataset and provenance will serve the correct version of the eBird dataset 633
we referenced. When archives and their URLs are eventually retired, 634
datasets and provenance can be copied to other archives without 635
compromising existing references, as long as their new locations are made 636
available in an openly accessible hash registry such as hash-archive.org. 637
Note that our Internet Archive publications (Poelen 2019a,b,c) contain 638
datasets and provenance only for the data collected from March 2019 639
through October 2019, whereas our Zenodo publications (Poelen 2020a,b,c) 640
contain only provenance for March 2019 through May 2020. 641

Several biodiversity data aggregators, such as GBIF and iDigBio, 642
produce a citation file for each user query to allow researchers to simply 643
reference a single citation file rather than each individual dataset (GBIF 644
2019, iDigBio 2016). A citation file lists the URLs, attributions, and 645
retrieval dates of the datasets that were returned by a query. We have 646
demonstrated that dataset URLs are unreliable references; thus, citation 647
files that rely on URLs as references are also unreliable. Citation files could 648
be made reliable if they were augmented with the hashes of the retrieved 649

datasets and, optionally, their provenance records. In fact, citation files
themselves can be referenced by hash, along with accompanying
provenance hashes, as long as they are archived and made accessible.

DOIs for Datasets and Queries

Biodiversity data aggregators often assign each dataset or query a Digital
Object Identifier (DOI) (Paskin 2009) (e.g., 10.123/456) wrapped as a
URL (e.g., <https://doi.org/10.123/456>) and advise researchers to reference
the generated DOI rather than a URL. Unfortunately, this abstraction
does little to enhance the reliability of the reference.

The DOI System (Paskin 2009) uses the Handle System (Sun et al.
2003) to resolve DOIs to online resources. However, it does not enforce any
constraint on type of resource associated with a DOI. When DOIs are used
to reference biodiversity datasets, the associated resources are often URLs,
and therefore the use of such DOIs can be as unreliable as using URLs. In
practice, these DOIs identify the evolving dataset (or set of datasets in the
case of a query) rather than a fixed version, as demonstrated in the
example references above. It is possible that an author would wish to make
such a reference to an evolving online digital object. For example, an
author promoting use of a published dataset might want future users to be
directed to the most up-to-date content. However, such a fluid reference is
not appropriate for making published results reproducible.

The Handle System allows for a complex web of redirection and
distributed responsibilities. Just as the Domain Name System resolves
domain names in URLs to IP addresses, the Handle System allows
“handles” such as DOIs to be resolved to URLs. However, the responsibility

for resolving DOIs to URLs is divided between the Handle System and
DOI registrars. The Handle System serves as the central authority that
maps DOI prefixes to DOI registrars, examples of which include BHL,
DataONE, and GBIF. These registrars are responsible for associating DOIs
that match their designated prefix with URLs, and are free to change the
URL associated with any given DOI under their jurisdiction (IDF 2018,
Paskin 2009).

The ability of biodiversity aggregators and providers to change the URL
associated with a DOI is good for reference reliability in the sense that
they can account for dataset migration without compromising existing
references. However, the use of DOIs addresses neither the instability of
the URLs they redirect to nor cases of link rot in which no URLs remain
responsive to serve the referenced dataset. Additionally, as the number of
datasets identified online continues to grow, proper maintenance of all of
the DOIs an aggregator or provider administrates might become more
unsustainable over time, potentially increasing the risk of unreliable URLs
going undetected.

In an article proposing HTTP-URI-based stable identifiers (e.g., URLs
that are resolvable over HTTP) for biological collection objects, Güntsch et
al. admit that the use of DOIs does not solve the problem of unreliable
referencing but merely deflects the burden of URL maintenance onto
institutional repositories (Güntsch et al. 2017). In contrast, we propose a
dataset referencing scheme that is reliable and can be supported by existing
infrastructures and workflows. If existing workflows require references to
be in the form of DOIs, it could be convenient to embed content hashes
into DOIs. Such an approach has already been established for ISBNs

through the creation of actionable ISBNs, or ISBN-As (Weissberg 2008),
which may serve as a model for actionable content hashes.

What It Means to Preserve Data

Our results indicate that reference rot threatens the integrity of published biodiversity datasets. We have seen that the use of content-based identifiers can effectively address the issue of reference rot. However, identifiers are of little use in a vacuum. An identifier can only be useful for data retrieval when combined with a resolver to associate identifiers with locations and a database to retrieve the dataset at the associated location (Paskin 1999). Thus, we need to address how resolvers and databases might be organized to accommodate content-based identifiers in order to fully realize long-term data preservation. In this context, we define data preservation as the continued capacity for datasets to be reliably referenced and retrieved in their original form even as the global digital biodiversity network evolves over time.

We propose four requirements that must be met to ensure proper data preservation: 1) datasets must be addressable and retrievable using content-based rather than location-based identifiers; 2) an agent must exist to collect datasets, record their provenance, and deposit both to a dedicated repository; 3) these repositories should archive data that could be used in the future; and 4) content hash registries should be openly accessible to resolve hash identifiers to dataset locations within such repositories. Although openly accessible registries should make archived data discoverable, access to those data can still be restricted. Additionally, for the purposes of archiving, it is important that the recorded provenance

records do not describe the datasets themselves, but rather the activities
that led to the procurement of those datasets; the primary purposes of
provenance in the context of an archive are to document the fact that
evidence (i.e., an observation of a dataset) does exist and to make it
discoverable for interested users (Bearman 1995).

We have shown that software agents such as Preston can be used to
collect datasets and their provenance over time while maintaining
content-addressability; all that is needed to ensure proper data
preservation are a dedicated repository and an openly accessible content
hash registry to map content-based identifiers to datasets located in the
repository. In practice, repositories and registries (and potentially software
agents such as Preston deployments) can be colocated; examples include
Zenodo and the Internet Archive, although they impose some limitations
that may restrict file size, number of files, and the amount of information
that can be indexed (Internet Archive 2019, Zenodo 2019). Zenodo and the
Internet Archive may serve as models for long-term biodiversity
information systems.

These four requirements help to ensure that biodiversity data remain
FAIR (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al.
2016). Findability is achieved through the publishing of provenance logs
that thoroughly describe what datasets are and where they were retrieved.
The amenability of the content-based identification paradigm to the
operation of independent decentralized repositories strengthens
accessibility by preventing the failure of a single data repository from
inhibiting future data access (see figure 4). Content-based identification
also contributes to interoperability across data networks due to the

absence of any central authority to administrate data access; a content
hash computed from a dataset is guaranteed to match the hash computed
by any other agent using the same dataset. Furthermore, content-based
identifiers can be embedded in or referenced by DOIs to maintain
compatibility with systems that use DOIs as identifiers. Finally, and
particularly relevant to this paper’s purpose, reusability is strengthened by
enhancing the retrievability of referenced datasets and allowing users to
verify that a retrieved dataset exactly matches that which was referenced.

Future Work

The fourteen-month span of our experimental results might not be
considered long-term in the context of biodiversity data. To evaluate the
long-term reliability of provider network URLs in the aggregators,
continued monitoring is needed.

Although we only monitored the provider networks of each aggregator,
the same methods used in this paper to monitor URLs, collect datasets,
and record provenance could be used for any of the URLs in biodiversity
data networks.

In this study, we only monitored URLs that locate datasets. However,
datasets may internally contain references to other data, such as media,
literature, and genetic sequence information (Wieczorek et al. 2012). Such
references are often URLs and therefore potentially unreliable. For
datasets that contain links to other data, a recursive approach could be
considered where those links are themselves queried for content and
tracked through provenance records. This is the subject of future work and
beyond the scope of this paper.

Conclusions

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Although reference rot is resulting in a steady decline in the reliability of
our digital biodiversity record, realistic solutions are available to address
the root causes of the issue. Content drift can be eliminated altogether by
changing the way we reference datasets from using location-based
identifiers to ones that are content-based. Meanwhile, the biodiversity
provider networks can be made more resilient to link rot if decentralized
observation, archiving, and distribution techniques are used to capture
incremental changes to the data record so that references can remain valid
even when online datasets are updated, removed, or relocated. The use of
content-based identifiers should be considered by biodiversity data
aggregators in order to increase the reliability of references to the data
they aggregate.

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We have demonstrated that data observatories can be deployed to track
the growing digital biodiversity data record. Using the dataset provenance
collected over a period of fourteen months, we were able to quantify the
change in reliability over time in terms of link rot and content drift
exhibited by the provider network URLs registered in major biodiversity
data aggregators. Even if aggregators and providers uniformly adopted
content-based identification of datasets and maintained versioned datasets,
our method of quantifying link rot and content drift in data networks
could be used to monitor whether either of these issues persist in practice
due to implementation flaws or nontechnical issues.

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Biodiversity data observatories can also be used to increase the
longevity of the biodiversity data record. Such observatories can be used
to form reliable dataset references as well as recover datasets that would

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otherwise become inaccessible due to link rot and content drift. 803
Additionally, the dataset provenance captured by such observatories serves 804
as evidence of the evolution and distribution of the digital biodiversity 805
data record. The combination of archived datasets and provenance can 806
ensure the long-term reproducibility of scholarly works that reference 807
ever-evolving biodiversity datasets. 808

Furthermore, the establishment of dedicated data repositories and 809
publicly accessible content hash registries are beneficial for making 810
content-addressed biodiversity data discoverable, distributable, and 811
long-lived, by securely archiving the datasets and provenance captured by 812
biodiversity data observatories and making them publicly available. 813

Great care has been taken to establish rigorous preservation guidelines 814
for physical specimens, yet there is much that can be done to increase the 815
longevity of our digital data. Our method is not only suited for tracking 816
datasets in biodiversity data networks, but also provides a resilient and 817
reliable way to publish, reference, and preserve scientific digital datasets 818
without having to abandon our existing infrastructures. The method 819
provides a much-needed foundation for constructing digital provenance 820
graphs from an accessible, verifiable, and citable digital scholarly record. 821

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