Universidade do Minho
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Ex-Situ Geoheritage Case Study: Quantitative and Qualitative Analysis of the Uppsala University Museum of Evolution Collections

setembro de 2024

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Doutor Jan Ove R. Ebbestad

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Statement of Integrity

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Ex-Situ Geoheritage Case Study: Quantitative and Qualitative Analysis of the Uppsala University Museum of Evolution Collections

Abstract

Natural history museums operate at a complicated intersection between museum studies, geology, biology, and culture. Museum collections are vital to natural science disciplines, yet they often face constraints in funding, space, and personnel, which limit their capacity to manage collections effectively. Ex-situ geoheritage is an emerging subfield of the wider geological heritage and geoconservation movements. Although it shares principles with in-situ work, there remains a significant research gap in addressing the needs of ex-situ geological material. Integrating geoheritage and geoconservation practices into museum studies offers a promising framework to address these challenges while guiding future conservation, acquisition, and collection management efforts. This case study applies a geoheritage inventory and valuation methodology to the Uppsala University Museum of Evolution, Sweden, utilising qualitative and quantitative approaches. The methodology, adapted from da Silva, Mansur, and de Costa (2023), was tested on 417 items to assess the content and value of the specimens. After cataloguing, the material was graded on fifteen valuation criteria, divided into two categories — Popularisation and Collections — to differentiate between the varying values of the geological material. While the inventory performed well, significant challenges in cataloguing older museum collections were highlighted. For example, 49% of items lacked easily accessible age data, and 12% were missing acquisition information. Specimens were ranked by fossil group and average valuation scores using RStudio. In the valuation, groups such as Belemnites scored poorly, suggesting areas for targeted improvement and acquisition, whereas Trilobites exhibited mixed valuation results, implying some capacity for the prioritisation of better-ranked specimens. The data also revealed that high performance in one valuation category did not necessarily correlate with success in the other, emphasizing the need for a multifaceted approach. Additionally, a conservation review was conducted, reviewing fourteen conservation parameters across 22,070 items. This review exposed significant gaps in conservation practices, such as low rates of new labels and collection numbers. Critical areas for improvement were identified, such as the under-conserved Skanian and Palaeozoic collections. The combined results demonstrate the benefits of conducting qualitative and quantitative reviews using geoheritage methodologies in museum collections. The results underscore the need for further development of ex-situ geoheritage methodologies to enhance museum practices and foster inter-institutional collaboration.

Keywords: Geoheritage, Museums, Geological Inventories, Conservation

Estudo de caso de património geológico ex-situ: análise quantitativa e qualitativa das coleções do Museu de Evolução da Universidade de Uppsala

Resumo

Os museus de história natural operam numa complexa intersecção entre os estudos museológicos, a geologia, a biologia e a cultura. As colecções de museus são vitais para as disciplinas das ciências naturais, mas enfrentam frequentemente restrições de financiamento, de espaço e de pessoal, o que limita a sua capacidade de gerir eficazmente as colecções. O geopatrimónio ex-situ é um subcampo emergente do património geológico mais vasto e dos movimentos de geoconservação. Embora partilhe princípios com o trabalho in-situ, continua a existir uma lacuna significativa de investigação na abordagem das necessidades de material geológico ex-situ. A integração das práticas de geopatrimónio e geoconservação nos estudos museológicos oferece uma estrutura promissora para enfrentar estes desafios, ao mesmo tempo que orienta os esforços futuros de conservação, aquisição e gestão de coleções. Este estudo de caso aplica uma metodologia de inventário e avaliação do património geológico ao Museu da Evolução da Universidade de Uppsala, na Suécia, utilizando abordagens qualitativas e quantitativas. A metodologia, adaptada de Silva, Mansur e Costa (2023), foi testada em 417 itens para avaliar o conteúdo e o valor dos exemplares. Após a catalogação, o material foi classificado em quinze critérios de valorização, divididos em duas categorias – Popularização e Colecções – para diferenciar os valores variados do material geológico. Embora o inventário tenha tido um bom desempenho, foram destacados desafios significativos na catalogação de colecções de museus mais antigas. Por exemplo, 49% dos artigos não tinham dados de idade facilmente acessíveis e 12% não tinham informação de aquisição. Os espécimes foram classificados por grupo fóssil e pontuações médias de avaliação utilizando o RStudio. Na avaliação, grupos como os Belemnites tiveram uma pontuação baixa, sugerindo áreas para melhoria e aquisição direcionadas, enquanto os Trilobites exibiram resultados de avaliação mistos, implicando alguma capacidade para a priorização de espécimes melhor classificados. Os dados revelaram também que o elevado desempenho numa categoria de avaliação não se correlacionava necessariamente com o sucesso na outra, enfatizando a necessidade de uma abordagem multifacetada. Além disso, foi realizada uma revisão de conservação, analisando 14 parâmetros de conservação em 22.070 items. Esta revisão expôs lacunas significativas nas práticas de conservação, tais como baixas taxas de novos rótulos e números de recolha. Foram identificadas áreas críticas para melhoria, tais como as colecções subconservadas do distrito da Escânia e da Era Paleozóica. Os resultados combinados demonstram os benefícios da realização de análises qualitativas e quantitativas com recurso a metodologias de geopatrimónio em coleções de museus. Os resultados sublinham a necessidade de um maior desenvolvimento de metodologias de geopatrimónio ex-situ para melhorar as práticas museológicas e promover a colaboração interinstitucional.

Palavras-chave: Geopatrimónio, Museus, Inventários Geológicos, Conservação

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1. Introduction

1.1 Ex-situ heritage within Geoheritage and Geoconservation

In recent years Geoheritage and Geoconservation have emerged as contemporary concepts founded on recognising the inherent cultural and scientific values of geological features, alongside a desire to record and preserve sites and features of interest. The fields aim to highlight and work towards protecting the broad diversity of natural features and landscapes, including sites and specimens of geological interest, processes, and geomorphological features for the use and enjoyment of future generations (Prosser, 2013).

Since the 1950's there has been a surge in the number of researchers and organisations dedicated to establishing the importance of geological diversity and features as being worthy of legal protections and conservation on-par with biological sites and biodiversity (Reynard and Brilha, 2018). The 20th Century saw pivotal advances in these concepts, exemplified by international initiatives such as UNESCO World Heritage (1972), GILGES (1988), and ProGeo (1993). Over time, progress has only continued, heralded by the establishment of the Global Geoparks Network (2004), the inaugural publication of the journal 'Geoheritage' (2009), and the IUGS Commission on Geoheritage (Brilha and Reynard, 2018).

This recognition of geology as unique and culturally significant has prompted institutions and practices dedicated to developing work in the active management and protection of geoheritage sites, which are now yielding positive results. These practices often involve a combination of scientific and cultural management strategies aimed at mitigating threats to geological features, such as inventories, valuation methodologies, and more (Reynard and Brilha, 2018). As a result of decades of valorisation campaigns, it is now generally well established that in-situ geological material, features, and processes are conservation-worthy and maintain inherent heritage value due to their scientific, socioeconomic, and educational value (De Wever and Guiraud, 2018; Reynard and Brilha, 2018). Despite these successes, there remains a significant gap in recent geoheritage and geoconservation work - that of ex-situ geoheritage (Van Geert, 2019).

Ex-situ geology refers to geological material removed from its original context, for example fossils, minerals, and rocks which now inhabit collections, laboratories, or elsewhere. Like in-situ geology, ex-situ objects can possess heritage value through a combination of inherent and subjective factors. Endere and Prado (2015) discuss ex-situ geological material as 'non-renewable scientific resources', with an intrinsic heritage value due to their scientific and cultural significance (Henriques and Pena dos Reis, 2015). Ponciano et al. (2011) highlight the cultural elements of ex-situ geological material, discussing ex-situ geological heritage not just as the materials themselves, but also associated with collection records such as maps, field notebooks, replicas, and art (da Silva et al. , 2023). Invariably, the value sourced from ex-situ geological collections is immense, therefore there are a plethora of museums, educational programmes, research, and legal frameworks centred around ex-situ geology (De Wever and Guiraud, 2018).

What determines the value of ex-situ material in a geoheritage context is debated. Thomas (2012) argues for the heritage values of palaeontological material as representations of the unique diversity and changing nature of Earth's history (Henriques and Pena dos Reis, 2015). Using this logic, every example of geological material may be considered as worth preserving as a unique piece demonstrating the diversity of the earth. However, like in-situ geology, organisations have limited resources to attribute to the preservation and storage of material. De Wever and Guiraud (2018) discuss the numerous challenges facing museum collections of ex-situ material, specifically noting that they cannot grow indefinitely. Therefore, the material must be subject to valuation, selection, and preservation based on its economic, scientific, educational, and cultural merits (Henriques and Pena dos Reis, 2015).

However, the development of such methodologies and the promotion of ex-situ geoheritage as a significant field of research has faced several challenges. The early valorisation of ex-situ geological material has been counter-productive in establishing consistent, modern principles and practices between the institutions that manage geological material, with museum studies methods strained alongside barriers like ownership laws, institutional bureaucracy, and ethical conflicts (Prosser, 2013; De Wever and Guiraud, 2018). Additionally, many laws surrounding geoconservation are only tailored towards the practicalities of materials and scientific services provided by geosites, or around conservation of at-risk sites (Henriques and Pena dos Reis, 2015), and many countries have not yet developed specific legal protections for geological material after removal from the original context (Page, 2018; De Wever and Guiraud, 2018).

1.2 Collections in Geoparks vs. Museums

Museums and geopark collections provide differing contexts through which to look at the application of geoheritage to collections (Van Geert, 2019). The two generally have different objectives and practices, although this gap is narrowing as geoheritage is popularised.

Natural science research has historically been based on the comparison and description of material from museum collections, therefore museums often have numbers of specimens unmatched by other fields (De Wever and Guiraud, 2018). The value of collections from a variety of strata, locations, and ages is huge, and general reference pieces are important due to their ability to allow cross-examination and correlation of past research (De Wever and Guiraud, 2018). Over time the scientific and cultural values of museum collections have grown, both in terms of research output and as educational and cultural centres. As ideas of heritage have spread, collections have become regarded as inherently valuable (de Lima and Carvalho, 2020). Consequently, practices are developing alongside these ideals, for example, destructive sampling is less permitted and extensive paperwork must be completed for loans and testing (De Wever and Guiraud, 2018). While geoheritage is less utilised in museum collections, this gap is lessening over time as geoheritage education spreads (Van Geert, 2022).

In contrast, museums within geoparks are more often targeted at providing education based on the unique features of the geology of the region, allowing specimens to be used in talks and workshops or as aesthetic display items in geopark centres (Van Geert, 2022). In this case, their motivations are centred with the valorisation of geological heritage and patrimony to connect the scientific and educational value of a specimen with its cultural, historical, or aesthetic appeal. Geoparks promote the community's cultural 'treasures', and use these to provide justification for the museum's existence and financial support (Van Geert, 2022). In this scenario, the geological material is presented in connection with the locality, region, collector, or researcher, lending more consideration to the cultural aspects of the specimens rather than scientific or financial value, which is often prioritised in general museums. As interpretation centres, they often engage with tactile and didactic exhibitions such as 3D models, fossil show-and-tell, and interactive panels which have only recently become more common in museum practices (Van Geert, 2022).

Correctly categorising geological material for Geoheritage purposes while maintaining the usefulness of the collection for general museum conservation is a difficult task (Van Geert, 2022). There is an apparent disconnect between geoheritage and geoconservation in different collection contexts, with many geological parks not having or maintaining geological exhibitions to museum-quality standards and museologists often unaware of the concept of geoheritage (Van Geert, 2022). This demonstrates the necessity for popularised, combined practices accounting for the needs of both geopark museums and large-scale museum collections.

1.3 Ex-Situ Geoheritage and Geoconservation Research

Henriques and Pena dos Reis (2015) discuss ex-situ material, specifically fossils, as a conduit between geoconservation and museum studies where the best practices can be amalgamated for the advancement of both geoconservation and the institutions storing and protecting ex-situ heritage items. Earth science collections take many forms implying a broad spectrum of potential value, including holotypes, type specimens, and other reference pieces, as well as low-value material (De Wever and Guiraud, 2018). As previously discussed, standardised practices are necessary to document, value, and organise geological resources in order to counter the limited resources available to the variety of institutions working with in-situ or ex-situ geological material. Such variability requires flexible inventory practices, and as much is recommended by Brilha (2018), who argues that each location or collection should have an adapted inventory. This enables the practitioner to reasonably take into consideration the main values which may be assigned to the geological material when designing the inventory. Consequently, there are several methodologies designed for the assessment and cataloguing of in-situ geological material, the most widely-used being that of Brilha (2016, 2018).

For ex-situ heritage, however, there appears to be a systematic disregard for ex-situ geological material as essential to geoheritage and geoconservation. In some cases, ex-situ geoheritage is essentially missing from publications discussing Geoheritage. In a 2020 analysis of the largest topical journal *Geoheritage,* Van Geert (2019) identified a scarcity of literature addressing themes related to museums and patrimony in a geoconservation and geoheritage context, identifying only four articles out of a total of 343 from 2009-2014. In addition, from 2013-2019 the International Journal of Geoheritage published no articles addressing ex-situ heritage in museums (Van Geert, 2019). Consideration for ex-situ material is also often disregarded in entire definitions of geoconservation, despite the necessity of ex-situ collections. For instance, Henriques *et al.* (2011) state '*The main purpose of geoconservation is the conservation of geosites as basic units of the geological heritage through the implementation of specific inventory, evaluation, conservation, valuation and monitoring procedures*." Other authors such as Brilha acknowledge the inclusion of ex-situ geoheritage as fundamental to geoheritage concepts, stating: '*To conclude [...] the main scope of geoconservation is the management of sites and ex-situ valued geodiversity elements by means of specific inventory, evaluation, conservation, valuing, and monitoring procedures*' (Brilha, 2018). However, in the same publication, ex-situ geoconservation is not mentioned once in the final chapter regarding future work, despite the evident ex-situ research, methodological, and legislative gaps discussed earlier in the same work, pointing to the systemic oversight of this topic (De Wever and Guiraud, 2018).

Subsequently, methodologies for quantitative assessments of ex-situ geoheritage collections are limited. With regards to in-situ assessment methodologies, some have been tailored specifically to include palaeontological criteria, for example the Palaeontological Index within the Geodiversity Index proposed by Pereira *et al.* (2013), and Bruno *et al.*'s (2014) classification for palaeontological geosites (Henriques and Pena dos Reis, 2015). While valuable for in-situ assessments, these methodologies do not account for the geoheritage material after removal from the site. This limitation is acknowledged by Henriques and Pena dos Reis (2015), who note that geosites can be of interest because of their palaeontological or mineralogical content, some of which is almost always removed for scientific study. If a geosite is valuable for its palaeontological or mineralogical finds, it can be assumed that the material maintains its value after removal from the geosite, however there remains a lack of robust inventory and assessment methodologies suitably accounting for the movable qualities of geoheritage (da Silva, Mansur, and de Costa, 2023).

Pena dos Reis and Henriques (2009), Haag and Henriques (2016), Fidalgo and Fernández-Martínez (2021), and da Silva et al. (2023) are the only four articles to have developed and applied qualitative methodologies solely for the valuation of ex-situ geological heritage, integrating attributes beyond the scientific elements of geoheritage to incorporate the cultural values associated with collection items (da Silva *et al.,* 2023). Due to the large differences between in- and ex-situ heritage, combined inventories such as that of Endere and Prado (2015) may be inappropriate to fully consider the unique heritage attributions of collections and are not discussed forthwith.

Pena dos Reis and Henriques (2009) produced one of the first qualitative evaluation systems capable of considering both in- and ex-situ heritage by qualifying the geological heritage and socio-cultural value for evaluation purposes, allowing site-based and specimen-based evaluation procedures to be adapted for all types of geological material (da Silva *et al.,* 2023). This was later updated and applied by Haag and Henriques (2016) to assess the geoheritage value of a university collection in Amazonia, Brazil. Adaptable inventories like this are important, as organisations are able to consider their collections using a range of values, allowing them to tailor displays and educational programmes using the items with the highest geoheritage value.

Such methodologies are useful in attributing diverse properties to ex-situ material however, they favour holistic assessment methods over the objective, numerical structure typical to modern in-situ geoheritage methodologies. This specialised system has been criticised for its unrelatability to the public, and may be difficult for those without a geoheritage background to apply (da Silva *et al.,* 2023). Despite its applicability to collections, holistic parameters such as *Abstract Perceptiveness* (the public understanding of such meanings in relation to the social use of the fossils) and *Relevance Grade* (the meaning attributed to the fossils by scientific communities) may not be comprehensive enough to be used independently for museum collections and the varying needs arising from the intersection of geology and museology (da Silva, Mansur, de Castro, 2023). Such an inventory should be beneficial not only from a geoconservation perspective, but provide value to the museums themselves. Holistic approaches may not be as valuable to museums as objective ones, which can also offer solid numerical data for uses beyond heritage evaluations.

The approach taken by Fernández-Martínez (2021) includes a scientific-historic review alongside a proposal of valuation criteria. The criteria were developed under the consideration that collections are often not complete or, well conserved, and lack information. The inventory is composed of nine criteria, specific to the context of the specific collections (including *Map No.*), thus allowing an analytical breakdown of the collection by category. For the heritage evaluation, a selection of seven of the criteria from Endere and Prado (2015) were adapted and given parameters and grades from 0-2. While this was a more thorough numerical assessment than the other inventories, the use of only seven criteria of three parameters each to grade ex-situ geoheritage may fail to fully encompass all the considerations that come with such varied material.

Despite only being tested on twelve items in the Museu da Geodiversidade in Rio de Janeiro, Brazil, the inventory and valuation methodology proposed by da Silva *et al.* (2023) is extremely comprehensive and encompasses a much wider range of values than other methodologies. The inventory appears to be relatively standard similar to the current inventory procedure at the Uppsala University Museum of Evolution, and following museological documentation recommendations posited by Ferrez (1994) with the exception of additions for geoheritage evaluations such as 'Use' and 'Theme'. The valuation criteria are cleverly divided into two, a value for Collections and a value for Popularisation. This allows for museums undertaking the valuation to acknowledge and valorise the differences in geoheritage material without devaluing items based on their scientific or aesthetic values. For these reasons, the methodological proposal by da Silva, Mansur, and de Costa (2023) was chosen for analysis in this work.

1.4 Aims

Evidently, numerous questions remain regarding ex-situ geoheritage, including its position within or adjacent to geoheritage and geoconservation principles and practices, the potential for bridging the gap between museum studies and geoscience through the application of geoheritage practices in museums, and addressing the significant research gap in ex-situ geoheritage inventories and valuation methodologies.

Considering the above, this thesis seeks to address the research gap by investigating one methodological approach through a case study and analysis of the Uppsala University Museum of Evolution. The objectives of this work are:

- Test the viability of an ex-situ inventory methodology within a large-scale museum context;
- Explore the benefits of integrating geoheritage inventory practices within museums through a quantitative and qualitative review of the Uppsala University Museum of Evolution; and
- Affirm the advantages of applying geoheritage and geoconservation principles and practices to ex-situ geoheritage contexts.

2. Materials and Methods

The methodologies outlined herein are comprised of three parts; a qualitative inventory and valuation methodology, a quantitative review of the inventory and valuation results, and quantitative review of the conservation conditions of the collection. The results, as well as additional commentary, will also be provided in an internal document to the Uppsala University Museum of Evolution.

2.1 Inventory Methodology

The following inventory procedure is taken from da Silva *et al.* (2023), combining the preliminary practices of the MGeo Team in 2017 with recommended guidelines for museological documentation from Ferrez (1994) (Figure 1). This inventory covers the wide range of standard information accompanying geological material, as well as the cultural criteria relevant to Geoheritage practices such as 'Type' and 'Theme'. Criteria 12 and 13 were adapted for this study, switching 'Exhibitions' for 'Collections' as the material subject to inventory at the Museum of Evolution is only housed in the collections. Otherwise, all fields were considered appropriate for application in the following work.

Inventory fields (from da Silva *et al.,* 2023)	
1	**Name of the Piece:** name found on the label associated with the piece, or geological name when no label is present;
2	**Identification Number:** registration or foundation number of the piece in the collections to which they belong. This field is also a facilitator in data collection in the second phase of cataloguing;
3	**Type:** identification of geodiversity specimen type associated with the piece or the type of specimen;
4	**Composition:** composition of the piece, whether chemical, structural, or content information;
5	**Associated Age:** age associated with the piece, whether rock, fossil, or mineral, or the age related to the historical interaction with humans;
6	**Origin:** sample collection site;
7	**Mode of Acquisition:** regarding the form of acquisition of the piece: donation, direct collection, purchase, or loan;
8	**Use:** function associated with the identified use and contained in the information on the piece (civil construction, petroleum industry, mining, cultural)—being categorized into 4 types of use: scientific, didactic, symbolic, and economic;
9	**State of Conservation:** if it presents deterioration or loss of material. The concepts of "good," "regular," or "poor" were attributed to this evaluation;
10	**Bibliography:** if the piece is part of scientific research or if the specimen is part of a pre-existing research area;
11	**Associated themes:** aims to determine the geological themes associated with the piece (geological time, petrography, mineralogy, paleontology, geography, cartography, tectonics, evolution of life);
12	**Date of Observation in the Collection:** added with the intention of making available a data record for future research in the museum and monitoring;
13	**Current Location in the Collections:** this is recorded as the tray label of the cabinet of the collections room where the piece is housed;
14	**Observation:** for any additional information.

Figure 1 - Inventory fields from da Silva et al. (2023).

In this study the majority of inventoried specimens are from the Inventory Type Collection (INV). This collection was chosen as it is the largest and one of the most diverse at the Museum of Evolution, representing varied fossil groups from different Stages of Earth's history. Additionally, the ages of this collection best represent the complex needs and challenges signature to large museum collections that this study is designed to test against, for example accommodating the information availability for both modern and $19^{th}/20^{th}$ Century material. Four specimens from the Reference Collection were inventoried to examine the principles as applied to vertebrate material and invertebrate material from another collection, but ultimately the Invertebrate Type Collection was deemed sufficient to explore the nuances of applying the inventory to large-scale museum collections. Varied types of fossils were recorded to explore this. he majority of specimens selected for inventory were the best or only example of a species in the collections tray, but it also includes variations such as different types of casts, paratypes and holotypes, poorly preserved or conserved specimens, and incomplete specimens.

2.2 Valuation and Weighting Methodology

The criteria and parameters of the valuation methodology are taken directly from da Silva *et al.* (2023), wherein there are 12 criteria for the evaluation of value for Popularisation, and 8 criteria for the evaluation of value for Collections (Table 1, Table 2). In the original methodology there is a contradiction between the tables demonstrating the criteria and the given weights. '*Specimen Size'* is included in the weightings for the value for popularisation (5/100) but excluded from the methodological description and final scores. Later discussion with the author revealed that this was a publishing error and *'Specimen Size'* should be removed from consideration (da Silva, personal communication, 23^{rd} August, 2024). In this work however, the criterion of *'Specimen Size'* has remained included as the size of an item can be a large attractor for the general public and is significant for popularisation. Table 1 has been adapted in order to reflect this inclusion.

Each criterion is attributed four parameters ranking 0, 1, 2, and 4, where 0 is the lowest value and 4 is the highest. Each parameter is also accompanied by an 'indicator' – a written example of criteria that a specimen should meet to achieve a specific score (Table 1, Table 2).

Criteria, parameters, and indicators of the methodological proposal for quantitative valuation for ex-situ geological heritage in relation to value for popularization (Adapted from da Silva *et al.,* 2023)	
Criteria	**Points**
Accessibility—content of the piece accessible to the public in accordance with strategies of an instrumental, communicational, or architectonic nature	
Does not fulfill any of the 3 premises below	0
Has an accessibility strategy	1
Has two accessibility strategies	2
Has three or more accessibility strategies	4
Geoscientific content—indicates the relevance that the specimen illustrates in representing geoscientific content	
Does not fulfill any of the characteristics below	0
The fossil, petrological, and mineralogical characteristics are recognized by geoscientists	1
The fossil, petrological, and mineralogical characteristics require some form of mediation to be recognized	2
The fossil, petrological, and mineralogical characteristics are visually represented by the content associated with the specimen	4
Didactic potential—capacity of the specimen to be used and easily understood at various levels of teaching	
Does not fulfill any of the 3 premises below	0
Illustrates university curricular content	1
Illustrates curricular content of any school level or is being used in university-level didactic activities	2
Is used in didactic activities at any level of teaching	4
Diversity—quantity of geological elements with scientific interest	
The item has a single specimen of rock, mineral, or fossil	0
The item has more than one specimen of rock, mineral, or fossil	1
The item has specimens of mineral, rock, and fossil	2
The item has various specimens of mineral, rock, and fossil	4
State of conservation—conservation conditions of the specimen	
Specimen presents significant deterioration or is practically destroyed	0
Specimen has deterioration that impedes visualization of certain characteristics of interest	1
Specimen has some deterioration that does not significantly affect visualization of characteristics of interest	2
Specimen is well preserved, practically intact	4
Fragility—preservation conditions of the specimen	
Specimen with a preservation problem in lithology of easy preservation	0
Specimen with preservation problems in lithology of difficult preservation	1
Specimen without a preservation problem in lithology of easy preservation	2
Specimen without preservation problems in lithology of difficult preservation	4

Interpretation potential—capacity of the specimen to be interpreted by the public	
Does not fulfill any of the 3 premises below	0
Specimen clearly and expressively illustrates its geological importance and utility to specialists	1
Specimen clearly and expressively illustrates its geological importance and utility to any cultural level	2
Specimen is being used for exhibition activities	4
Rarity—quantity of specimens in collections and museums	
There are many specimens in collections in the country	0
One of the few known specimens in the country	1
Only known specimen in the region	2
Only known specimen in the world	4
Specimen size—referring to the dimensions of the specimen	
Specimen is smaller than usual	0
Specimen is similar to the usual	1
Specimen is larger than usual	2
Specimen is of giant size, notably larger than usual	4
Traditional and symbolic use—if the specimen presents traditional and/or symbolic uses. Understanding symbolic use as use of the element in religious or mystical practices; and traditional use as an element used as lithic tools at archeological sites or objects used by traditional populations or as part of internal and external decoration	
Specimen lacks traditional and symbolic use	0
Specimen that is or was used traditionally or symbolically	1
Specimen that is and was utilized traditionally or symbolically	2
Specimen that is and was used traditionally and symbolically	4
Industrial and economic use—if the specimen presents industrial and/or economic use	
Specimen lacks industrial and economic use	0
Specimen that is or was used industrially or economically Specimen that is and was used industrially and economically	1
Specimen that is and was utilized industrially or economically	2
Specimen that is and was used industrially and economically	4
Awareness raising potential—capacity to raise awareness of the public by connecting with popular imagination or by easily recognizable value	
The specimen is not part of the popular imagination and its geoscientific content is not easily recognized	0
The specimen is not part of the popular imagination or its geoscientific content is not easily recognized	1
The specimen is not part of the popular imagination, but its geoscientific content is easily recognized	2
The specimen is part of the popular imagination and its geoscientific content is easily recognized	4

Table 1 – Criteria, parameters, and indicators of value for popularisation (Adapted from da Silva et al., 2023).

Criteria, parameters, and indicators of the methodological proposal for quantitative valuation for ex-situ geological heritage in relation to value for collections (Adapted from da Silva *et al.,* 2023)	
Criteria	Points
Scientific Interest—indicates the relevance that the specimen illustrates in representing geological elements and processes	
Does not fulfill any of the following characteristics	0
Fossil of biostratigraphic or paleobiological interest; mineral of crystalstratigraphic interest or a good indicator of a crystalline system; rock representative of sedimentary environments or good sedimentary structures, igneous series or good igneous texture and facies, or good metamorphic texture	1
Fossil of biostratigraphic and paleobiological interest; mineral of crystalstratigraphic interest and a good indicator of a crystalline system; rock representative of sedimentary environments and good sedimentary structures, igneous series and texture and facies, and metamorphic texture	2
Holotype, lectotype, or neotypes, meteorites	4
Degree of Scientific Knowledge—existence of scientific publications and studies associated with or about the piece	
There are no studies or theses	0
There are published studies and/or theses	1
Cited in theses and published studies referenced in scientific periodicals of national relevance	2
Cited in theses and published studies referenced in scientific periodicals of international relevance	4
Rarity—quantity of specimens in collections and museums	
There are many specimens in collections in the country	0
One of the few known specimens in the country	1
Only known specimen in the region	2
Only known specimen in the world	4
Diversity—quantity of geological elements with scientific interest	
The item has a single specimen of rock, mineral, or fossil	0
The item has more than one specimen of rock, mineral, or fossil	1
The item has specimens of mineral, rock, and fossil	2
The item has various specimens of mineral, rock, and fossil	4
State of conservation—conservation conditions of the specimen	
Specimen presents significant deterioration or is practically destroyed	0
Specimen has deterioration that impedes visualization of certain characteristics of interest	1
Specimen has some deterioration that does not significantly affect visualization of characteristics of interest	2
Specimen is well preserved, practically intact	4
Specimen size—referring to the dimensions of the specimen	
Specimen is smaller than usual	0
Specimen is similar to the usual	1
Specimen is larger than usual	2
Specimen is of giant size, notably larger than usual	4
Origin—site from which the piece was removed	
Specimen from an unexhausted deposit, there being similar others not exhausted	0
Specimen from an exhausted deposit, there being similar others not exhausted	1
Specimens from an unexhausted deposit, there being similar others exhausted	2
Specimen from a single exhausted deposit, or a good specimen belonging to unique collections, or a meteorite	4
Fragility—preservation conditions of the specimen	
Specimen with a preservation problem in lithology of easy preservation	0
Specimen with preservation problems in lithology of difficult preservation	1
Specimen without a preservation problem in lithology of easy preservation	2
Specimen without preservation problems in lithology of difficult preservation	4

Table 2 – Criteria, parameters, and indicators of value for collections (adapted from da Silva et al., 2023).

The authors discuss various considerations surrounding the criterion weighting (da Silva *et al.,* 2023). In this case, the weighting is designed to highlight the non-scientific aspects of the geological material, as the authors felt that scientific value was perhaps overestimated in other methodologies when considering the value of an item as an exhibition piece, although still acknowledging that scientific value is an important and integral aspect of acquisition. Given that the methodology is geoheritage-based and is not designed only to highlight the scientific values of the material, the weightings of the original methodology are deemed suitable for the investigation forthwith (Table 3). Collections value and Popularisation value are weighted and recorded separately with the intention of maintaining equity between both values during the evaluation process (Table 3).

Weight attributions by criteria (Adapted from da Silva *et al.,* 2023)				
Criteria	**Scientific Interest**	**Weight**	**Exhibition Interest**	**Weight**
Accessibility			X	10
Scientific Interest	X	15		
Geoscientific Content			X	10
Didactic Potential			X	10
Diversity	X	10	X	5
State of Conservation	X	10	X	10
Fragility	X	10	X	5
Degree of Scientific Knowledge	X	15		
Origin	X	15		
Interpretation Potential			X	10
Rarity	X	15	X	5
Specimen Size	X	10	X	5
Traditional and Symbolic Use			X	10
Industrial and Economic Use			X	10
Awareness Raising Potential			X	10
Total	Collections Value	100	Popularisation Value	100

Table 3 – Respective weights of each criterion (Adapted from da Silva et al., 2023).

The mathematical element of the original methodology seemed to not follow the traditional rules of calculating a weighted score and normalising the data (Figure 2). Here the authors use a typical weighted score method (*criterionscore*criterionweight*), then divide it by a scaling factor of 40, following the in-situ methodology of ASGMI (2018) (Figure 2). This represents the weight (100) multiplied by the maximum possible criterion score (4) and is done in order to normalise the final number out of 10 (Figure 2). Calculating the score based on this gives a normalised score for the overall sum of the points obtained by an item in each valuation category, but no equation is given to account for the differing weights and scores of the valuation criteria.

A more appropriate mathematical methodology would individually calculate the weighted score for each criterion, then sum the result using a scaling factor corresponding to the individual maximum possible scores of each valuation criteria, in this case 48 for Popularisation and 32 for Collections. Additionally, the present methodology fails to clearly articulate that both *criterionscore* and *criterionweight* represent fractions of a total, e.g., *criterionscore* has a maximum score out of four, e.g., 0, 1, 2, or 4/4, and *criterionweight* is a fraction of 100, e.g. 10/100, 5/100, therefore a clearer breakdown of the equations may be more appropriate for a methodology designed for public use.

Original Equation (From da Silva *et al.,* 2023)
$\sum((criterionscore * criterionweight)/40)$

Figure 2 - Original equation (from da Silva et al., 2023).

Therefore, a new weighted average equation was developed using traditional weighted mean methodologies to clarify the authors work (Figure 3). For simplicity, *criterionscore* has been rephrased as the *grade* and *maximumgrade* for criterions, e.g. 0/4, 1/4, etc. *Totalpossiblescore* represents the maximum number of points achievable in each valuation, in this case 48 points for Popularisation and 32 points for Collections (Figure 3).

The resulting sum was then normalised using linear rescaling based on the *totalpossiblescore* for each value, allowing for more accurate comparison between the two values given their differing totals (Figure 4). This approach offers the benefits of practical presentation and more effective communication with non-geoscientists and others who may use the data.

The finalised data was input into RStudio for further data analysis (Appendix I), while basic table and graphs were made using Microsoft Excel.

New weighted average equation (From da Silva *et al.,* 2023)
$$weightedaverage = \sum((grade/maximumgrade) * totalpossiblescore) * (criterionweight/100)$$
$$w = \sum((g/m) * t) * (c/100)$$

Figure 3 – New weighted average equation.

New normalisation equation (From da Silva *et al.,* 2023)
$$\sum((weightedaverage/totalpossiblescore) * 100)$$
$$\sum((w/t) * 100)$$

Figure 4 – New normalisation equation.

2.3 Conservation Review Methodology

The collections of the Museum of Evolution are spread across multiple buildings and include a plethora of zoological, geological, and mineralogical items. Therefore, only a portion of material in the Museum of Evolution was evaluated in the following conservation review. This is comprised of the main collections area on the ground floor of the Museum of Evolution building. The ground floor of the Uppsala University Museum of Evolution houses 8 different collections rooms, 3 representing different periods of Earth's history and 5 representing collections based on type, collector, or location; the Palaeozoic Collection (PAL), Mesozoic

Collection (MES), Cenozoic Collection (CEN), Oversized Collection (OVS), Vertebrate Reference Collection (REF), Invertebrate Type Collection (INV), Skanian Collection (SKN), and the Sternberg Collection (STN).

Each collection room contains multiple cabinets or racks housing trays in which the geological material sits. In order to record the conservation status of the collections 14 criteria were recorded for each box or specimen in the collection (Figure 5, Figure 6a). These criteria are based on the internal collection and conservation practices at the Museum of Evolution in order to allow the museum to see where resources have already been distributed and where they are still required;

Conservation Criteria Adapted from Museum of Evolution internal document (Figure 6a)	
1	The number of boxes or specimens in the tray.
2	The presence of plastic protection on specimen labels.
3	The number of boxes containing items in need of remedial conservation.
4	The number of labels in the most recent, typed format.
5	The number of typed labels in old formats.
6	The number of handwritten labels, or boxes without labels.
7	The number of boxes with no or old collection numbers.
8	The number of items with a PMU assigned.
9	The number of items in old boxes or no box where there could be one.
10	The presence of literature in the tray.
11	The number of missing specimens.
12	The presence of red dots on items or labels, representing type specimens.
13	The presence of photographs or illustrations in the tray.
14	Empty or inaccessible trays.

Figure 5 - Conservation Criteria, adapted from Museum of Evolution criteria (Figure 6a).

The data was organised and recorded on a tray-by-tray basis in Microsoft Excel to allow for easy data analysis by collection, and to maintain open access for the museum staff. The data was summarised and compared using Microsoft Excel, which was also utilised in order to create tables and graphs. The collections undergo constant conservation work by curators and volunteers, as well as removal by researchers, therefore it should be considered that the conservation review records a snapshot in time and may not be representative of the most recent figures.

It should be noted that some boxes contain multiple specimens, often very small fossils or slides, but have only one label or *PMU* (newly assigned museum number meaning ‘Palaeontological collection at the Museum of Evolution). Similarly, some larger boxes contain fossils from the same animal with multiple labels and *PMU* numbers. In order to maintain the highest degree of accuracy with the rest of the criteria, criterion one was determined on a tray-by-tray basis based on the material inside.

Differentiation is made between *New Labels* in the most recent format and older *Typed Labels* (Criteria 4 and 5) because of the information present. Older, typed labels often lack the same information as the new ones such as *PMU's* and do not have English translations which would make the labels more accessible to a wider audience and link the item to its digital record (Figure 6b, 6c).

Criterion 5 was recorded based on the information provided with the *Typed Label.* For example, if only a typed number was present, the label did not meet the criteria, however, the presence of other identifying information such as species name or collection locality made the item eligible. In criterion 6, boxes with handwritten labels or a lack of label are grouped together due to the poor accessibility of the information. In many cases the handwritten labels are unreadable to the untrained eye, making them inaccessible and untranslatable even if they contain significant information (which most do not).

Criterion 11 encompasses all the ways that missing specimens are noted, including empty boxes, paper slips reading 'Missing', and pink slips which note if an item has been placed in the exhibition or moved to the conservation lab. Items missing without any indication have not been considered in this data.

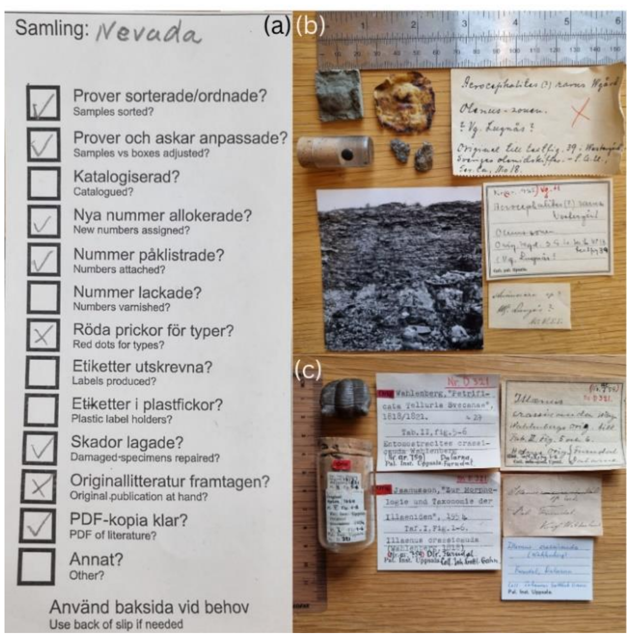

Figure 6 – Images, (a) Conservation slip from the Uppsala University Museum of Evolution, (b) Example of an item in poor condition with handwritten labels, old accession numbers, (c) Example of an item in good condition with old typed labels.

3. Results

3.1 Inventory and Valuation Results

In total, 417 specimens were catalogued, 413 from the Invertebrate Collection, and 4 from the Reference Collection. The inventory encompassed 18 different categories of geological material; 1 fish (0.2%), 1 ichthyosaur (0.2%), 1 crustacean (0.2%), 2 belemnites (0.5%), 2 graptolites (0.5%), 3 nautili (0.7%), 3 sedimentary samples (0.7%), 4 bryozoans (1%), 4 echinoids (1%), 6 ostracods (1.4%), 6 cephalopod molluscs (Orthoceras) (1.4%), 10 gastropods (2.4%), 30 ammonites (7.2%), 34 brachiopods (8.2%), 41 corals (9.8%), 42 plant fossils (10%), 61 bivalves (14.6%), and 166 trilobites (39.8%). Almost half of the specimens (205, 49.2%) had no locality information. Sixteen specimens (3.8%) lacked an identification number, 51 specimens had no acquisition data (12.2%), 5 had no provenance information (1.2%), and 5 specimens were missing references to literature (1.2%) (Appendix II).

For the value for collections, scores ranged from 8.3 to 34.3, with a spread of 26 points across 12 nodes (Figure 7, Figure 9a, 9c). Each node corresponds to an interval of 2.2 points (Figure 9). In terms of value for popularisation, the scores ranged from 7.5 to 78.8, with a total spread of 71.3 points across 15 nodes (Figure 8, Figure 9b, 9d). Each node represents a 5-point interval (Figure 8). The average score is 17.4 for material valued for collections, compared to 37 for material valued for popularisation (Figure 7, Figure 8). The mode value for collections was a score of 14.9–17.1, encompassing 129 items (30.9%) (Figure 7). In contrast, the mode interval for value for popularisation was higher, at 27.5–32.5, containing 85 items (19.2%).

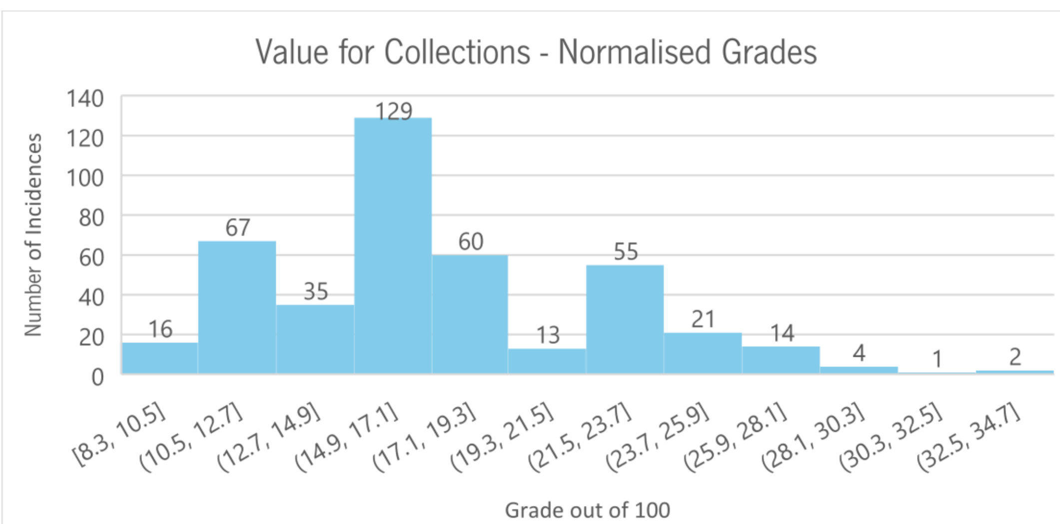

Figure 7 - Value for collections bar chart.

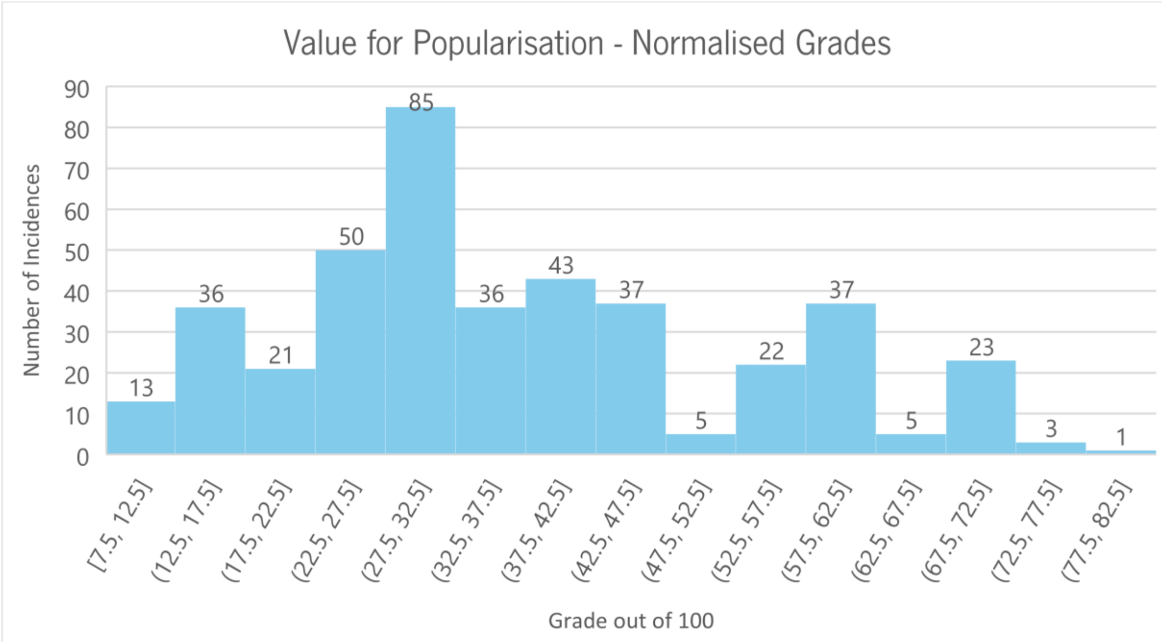

Figure 8 - Value for popularisation bar chart.

The highest- and lowest-scoring items within each category are ranked in Figure 8. Among the top-scoring items for Collections value, only two were also present in the top 10% of highest-scoring items for Popularisation: *Discoceras amtjaernense* (item 1) and *Isorthoceras sylphide* (item 5) (Figure 9a). Conversely, three items that scored highly in the Popularisation category also ranked within the top 10% for Collections: *Asaphus granulatus* (item 49), *Proteus concinna* (item 53), and *Pachycormus macropterus* (item 414) (Figure 9b).

Two items appeared in the rankings of the lowest-scoring items for both Collections and Popularisation value: *Halysites escharoides* (item 100) and *Ambonychinia semistriata* (item 344) (Figure 9c, 9d). These two items were the lowest-scoring in the Popularisation category (417th place). However, in the Collections rankings, they were jointly ranked 417th with two additional items, *Belemnites cylindricus* (item 42) and *Illaenus wimani* (item 240) (Figure 9c, 9d).

In all instances, multiple specimens share identical scores. Figure 8a shows 14 items tied for 8th place in the rankings for Collections, each with a score of 27.5. Additionally, 22 items are tied for 5th place in the Value for Popularisation category, each scoring 69.4 (Figure 9b). At the lower end of the rankings, 12 items are tied for 416th place in Collection value, each with a score of 10, while 11 items are tied for 416th place in Popularisation value, each scoring 9.4 (Figure 9c, 9d).

Item rankings by valuation scores (Appendix II)				
Highest Ranked Items for Collections				
(a)			Scores	
Ranking	Number	Item Name	Value for Collections	Value for Popularisation
1st	5	*Isorthoceras sylphide*	34.2	52.5
2nd	417	*Taramelliceras sp.*	34.2	37.5
3rd	1	*Discoceras amtjaernense*	32.5	61.9
4th	416	*Ammonite Aptychi*	30	43.1
5th	3	*Endoceras naekki*	29.2	33.8
6th	4	*Danoceras skalbergensis*	29.2	31.9
7th	6	*Halysites catenularius*	29.2	35.6
8th=	*14 items tied for 8th place*		27.5	
Highest Ranked Items for Popularisation				
(b)			Scores	
Ranking	Number	Item Name	Value for Popularisation	Value for Collections
1st	49	*Asaphus granulatus*	78.8	24.2
2nd	53	*Proteus concinna*	76.9	27.5
3rd	74	*Maeandrella cf. curvicollis*	76.9	22.5
4th	414	*Pachycormus macropterus*	71.3	24.2
5th	*22 items tied for 5th place*		69.4	
Lowest Ranked Items for Collections				
(c)			Scores	
Ranking	Number	Item Name	Value for Collections	Value for Popularisation
417th=	42	*Belamnites cylindricus*	8.3	11.3
417th=	100	*Halysites escharoides*	8.3	7.5
417th=	240	*Illaenus wimani*	8.3	11.3
417th=	344	*Ambonychinia semistriata*	8.3	7.5
416th=	*12 items tied for 416th place*		10	
Lowest Ranked Items for Popularisation				
(d)			Scores	
Ranking	Number	Item Name	Value for Popularisation	Value for Collections
417th=	100	*Halysites escharoides*	7.5	8.3
417th=	344	*Ambonychinia semistriata*	7.5	8.3
416th=	*11 items tied for 416th place*		9.4	

Figure 9 - (a) Highest ranked items based on Collections score, (b) Highest ranked items based on Popularisation score, (c) Lowest ranked items based on Collections score, (d) Lowest ranked items based on Popularisation score.

RStudio was used to illustrate the kind of information that can be extracted from completed inventories and valuations (Figure 10). A total of 25 items, representing 6% of the inventory, are found in the bottom 10% of scores for both Popularisation and Collections. Conversely, only 14 items (3.35% of the total inventory) appeared in the top 10% of scores for both values. Notably, there is no overlap between items in the bottom

10% of Collections scores and those in the top 10% of Popularisation scores, nor between items in the top 10% of Collections scores and those in the bottom 10% of Popularisation scores (Appendix II).

Figure 9a and 9b present the average rankings for Collections and Popularisation by category. *Orthoceras*, Ostracods, and Fish are the highest ranked categories for Collections value, with average scores of 30.3, 25, and 24.2, respectively (Figure 10a). In contrast, the highest average scores in Popularisation are achieved by Fish (71.3), Echinoids (51.9), and Gastropods (51) (Figure 10b). Nautili and Crustaceans are among the lowest-ranked categories for Collections, with average scores of 14.2 and 12.5, respectively (Figure 10a). In Popularisation, Graptolites and Nautili both score 28.1, ranking just above Belemnites, which have the lowest average scores in both Collections (9.55) and Popularisation (25.6) (Figures 10a, 10b).

Trilobites had the highest representation in the top 10% of Collections scores, with 9 specimens (5.4%), followed by ammonites and corals, each with 8 specimens, representing 26.7% and 19.5% of their respective totals (Figure 10c). In Popularisation, the categories with the most items in the top 10% are corals, trilobites, and gastropods, with 15 (36.6%), 13 (7.8%), and 7 (70%) items, respectively (Figure 10d). Eleven categories had only one item in the top 10% of scores in both Collections and Popularisation (Figures 10e, 10f).

Trilobites also had the highest number of poorly scoring items, with 56 specimens (48.3%) in the bottom 10% of Collections scores, and 32 specimens (19.3%) in the bottom 10% of Popularisation scores (Figures 10e, 10f). Ammonites rank second, with 7 items (23.3%) in the bottom 10% of Collections scores, while brachiopods rank second in Popularisation, with 5 items (14.3%) in the bottom 10%. Similarly, 11 categories had only one item in the lowest 10% of scores for both Collections and Popularisation (Figures 10e, 10f).

Fossil group rankings by average valuation scores (Appendix II)					
(a) Ranking by Average Collections Score			(b) Ranking by Average Popularisation Score		
1	Orthoceras	30.3	1	Fish	71.3
2	Ostracod	25	2	Echinoid	51.9
3	Fish	24.2	3	Gastropod	51
4	Bryozoan	24	4	Ostracod	45.6
5	Echinoid	23.1	5	Brachiopod	45.5
6	Plant	19.2	6	Plant	45.1
7	Coral	18.9	7	Coral	43.7
8	Ammonite	18.9	8	Ichthyosaur	43.1
9	Brachiopod	18.3	9	Bryozoan	41.7
10	Gastropod	18.3	10	Ammonite	41.3
11	Sedimentary	18.3	11	Orthoceras	40.8
12	Graptolite	17.1	12	Sedimentary	40
13	Bivalve	16.2	13	Bivalve	38.9
14	Icthyosaur	15.8	14	Trilobite	32.2
15	Trilobite	15.6	15	Crustacean	31.3
16	Nautilus	14.2	16	Graptolite	28.1
17	Crustacean	12.5	17	Nautilus	28.1
18	Belemnite	9.55	18	Belemnite	25.6
(c) Ranking by Number of Items with Scores in the top 10% for Collections			(d) Ranking by Number of Items with Scores in the top 10% for Popularisation		
1	Trilobite	9	1	Coral	15
2	Ammonite	8	2	Trilobite	13
3	Coral	8	3	Gastropod	7
4	Cephalopod	6	4	Ammonite	6
5	Ostracod	3	5	Plant	6
6	Bryozoan	2	6	Bivalve	4
7	Plant	2	7	Brachiopod	4
8	*Remaining Categories*	1	8	*Remaining Categories*	1
(e) Ranking by Number of Items with Scores in the bottom 10% for Collections			(f) Ranking by Number of Items with Scores in the bottom 10% for Popularisation		
1	Trilobite	56	1	Trilobite	32
2	Ammonite	7	2	Brachiopod	5
3	Coral	5	3	Coral	4
4	Bivalve	4	4	Bivalve	4
5	Gastropod	3	5	Belemnite	2
6	Brachiopod	2	6	Gastropod	1
7	Belemnite	2	7	Ammonite	1
8	*Remaining Categories*	1	8	*Remaining Categories*	1

Figure 10 - RStudio results. (a) Ranking by average Collections value score, (b) Ranking by average Popularisation value score, (c) Ranking by number of items with scores in the top 10% for Collections value, (d) Ranking by number of items with scores in the top 10% for Popularisation value, (e) Ranking by number of items with scores in the bottom 10% for Collections value, (f) Ranking by number of items with scores in the bottom 10% for Popularisation value.

3.2 Conservation Review Results

A total of 22,070 specimen boxes were counted across 1,750 trays within the eight collections housed on the ground floor of the Uppsala University Museum of Evolution, averaging at 12.6 boxes per tray (Table 4). Of these boxes, only 7,172 (32.5%) had labels with plastic protection and 3.8% of trays and specimens required some form of conservation. New labels were found on 10.58% of the collection, while older typed labels accounted for nearly twice that proportion, representing 19.07% of the total collection. However, handwritten or missing labels were by far the most prevalent label state, comprising 70.35% of the specimens.

Only 24.7% of items have been assigned new *PMU* numbers, leaving three-quarters of the collection (75.3%) with either no numbers or outdated ones. Additionally, 76.8% of items were stored in old boxes, with 5,129 items either housed in new boxes or not requiring one. Very few trays contained any associated literature (0.8%), and even fewer had accompanying photos or illustrations (0.5%). A total of 6,132 items were marked with red dots indicating they are type specimens, representing 27.8% of all items. Missing items accounted for 1.93% of the total collection. Finally, 248 trays were empty, representing 14.17% of the total number of trays (Table 4).

Table 5 displays the raw count data by collection. Each collection was then compared against the summary counts to determine which collections represented the highest and lowest proportions of the totals presented in Table 4. In Table 6, the strongest green indicates the highest percentages in each category, while the deepest red highlights the lowest. This reveals that the Invertebrate Type collection, as the largest collection, generally accounts for the highest proportion of the totals in each category. Conversely, the Oversized collection consistently represents the lowest proportions, reflecting its smaller size. The Invertebrate Type collection contains the highest number of trays, with 448 (25.6% of the total), followed closely by the Cenozoic collection with 411 trays (25.5%). The Oversized collection is the smallest, comprising just 36 trays, or 2.1% of the total (Tables 5 and 6).

In terms of plastic protection, the Mesozoic and Cenozoic collections account for 23.7% (1,698) and 23.5% (1,684) of the total, respectively, while the Invertebrate Type collection accounts for only 16.2% (1,164) (Table 6). The Cenozoic collection also has the highest number of specimens with handwritten or no labels, totalling 4,659 items, which represents 30% of the overall collection. The Reference collection has a disproportionately high amount of plastic protection on its specimens, representing 21.5% (1,542) of the total (Table 6). The

Cenozoic collection shows the smallest number of new labels and empty or inaccessible drawers, at 0.3% (8) and 0.46% (8) of the totals, respectively. Overall, the data indicates that the Palaeozoic, Reference, and Mesozoic collections occupy the middle range in terms of their percentages relative to the overall totals.

The individual breakdowns of each collection reveal a more varied array of results (Tables 5, Table 7). The Sternberg collection has the highest proportion of plastic protection at 94.6%, followed closely by the Reference collection at 94.1%. In contrast, the Skanian collection has the lowest proportion of plastic protection, covering just 0.2% of its total, followed by the Oversized collections at 1.5%. The Sternberg Collection has the highest level of conservation need, with 10.8% of the collection needing work. In comparison, the Reference, Oversized, and Palaeozoic collections each require conservation for a small fraction of their items, at 0.5%, 0.5%, and 0.6%, respectively (Table 7).

The Sternberg Collection also leads in the number of new labels, representing 95.7% of its total. This is significantly more than the next highest collections, the Vertebrate Reference Collection and the Mesozoic Collection, which have 19.6% and 18.2% new labels, respectively. The Skanian and Cenozoic Collections have the lowest rates of new labels, at 0.11% and 0.16% respectively. Many of the collections have high rates of Handwritten or No labels, notably the Oversized, Skanian, and Cenozoic collections, which have 96.5%, 96.9%, and 93.3% respectively. Typed labels are scarce across all collections, all having <9%, with the exception of the Invertebrate Type Collection where 40.35% of boxes have typed labels (Table 7).

The vast majority of the collections have high percentages of boxes with no or old numbers. The Skanian collections have the highest amount at 98.9%, followed by the Palaeozoic collection (89.9%), the Cenozoic collection (82.5%), and the Reference Collection (79.6%). The Sternberg collection has the lowest proportion of old numbers (4.3%), followed by the Oversized collection at 44.1%. Conversely, the majority of collections have few items assigned *PMU* numbers. The Skanian collection has only 1.1% of items assigned a *PMU*, far lower than the second-to-last Palaeozoic collection where 10.1% of items have a *PMU* (Table 7).

The collections with the highest percentages of old boxes are the Palaeozoic (98.2%), Reference (97.5%), and Skanian (95.4%) collections. The collection with the lowest percentage of old boxes is the Oversized collection (15.47%), followed by the Invertebrate Type collection (56.93%) (Table 7).

The Invertebrate Collections have the highest numbers of literature in the trays, 87, representing 19.4% of trays. The Sternberg and Mesozoic collections are almost tied for second place with 11.1% and 11.2% of trays containing literature respectively (Table 5, Table 7). The Oversized collection has the lowest proportion of trays containing literature, at only 2.8% of trays. All collections contain <20% of trays containing literature.

The Sternberg Collection has the highest percentage of missing items at 3.4%, many of which are on display in exhibitions. The Oversized collection has the lowest proportion of missing items (0.5%), followed by the Palaeozoic and Skanian collections at 1.3%. Although the Invertebrate Collection has the highest absolute number of missing items (211 individuals, representing 2.5% of the total), it is proportionally second to the Sternberg Collection (3.4%) (Table 5, Table 7).

The Oversized and Invertebrate Type collections have the highest percentages of specimens marked with red dots, indicating type specimens, at 50.5% and 46%, respectively. The Skanian Collection has red dots on only 0.2% of its items, followed by the Reference Collection at 8.3% (Table 7).

In some cases, there are photos and illustrations present in the boxes or trays, however this represents less than 11% in each collection, with the highest percentage being in the Reference Collection (10.4%). The Oversized collection contains only one Photo or illustration, representing 2.8% of trays. The Skanian and Sternberg collections also have a minimal number of photos or illustrations, with only 3 (1.6%) and 2 (4.4%) instances, respectively (Table 5, Table 7).

Finally, empty trays constitute significant proportions of certain collections, particularly the Invertebrate and Skanian collections, which consist of 25.89% and 24.60% empty trays, respectively. The Cenozoic Collection has the least empty space, at 1.95% of the total, followed closely by the Reference, Sternberg, and Oversized collections at 2.08%, 2.22%, and 2.78%, respectively.

Conservation Review - Summary Counts				
Criteria	**Total Count**	**Inverse Totals**	**Totals by %**	**Inverse Totals by %**
Total Trays	1750			
Total Boxes	22070			
Plastic Protection	7172	14898	32.50%	67.48%
Needs Conservation	871	21199	3.95%	96.13%
New Labels	2335	19735	10.58%	89.42%
Typed Labels	4208	17862	19.07%	80.91%
Handwritten/No Labels	15527	6543	70.35%	29.67%
Old Numbers	16622	5448	75.31%	24.69%
PMU assigned	5448	16622	24.69%	75.31%
Old Boxes	16941	5129	76.76%	23.17%
Literature Present	176	1574	10.06%	99.20%
Missing Specimens	427	21643	1.93%	98.06%
Red Dots for Types	6132	15938	27.78%	72.21%
Photos or Illustrations	110	1640	6.29%	99.51%
Empty or Inaccessible Trays	248	1502	14.17%	85.83%

Table 4 - Conservation Review Summary Counts. Raw numerical counts and the inverse totals, alongside the percentage totals and inverse percentage totals.

Conservation Review, Total Counts by Collection								
Criteria	**REF**	**OVS**	**PAL**	**INV**	**SKN**	**STN**	**MES**	**CEN**
Total Trays	144	36	203	448	187	45	276	411
Total Boxes	1638	202	1746	8403	2662	446	1983	4990
Plastic Protection	1542	3	653	1164	6	422	1698	1684
Needs Conservation	9	1	10	301	193	48	28	281
New Labels	321	2	159	1056	3	426	360	8
Typed Labels	127	5	150	3391	79	0	131	325
Handwritten/No Labels	1190	195	1437	3956	2580	20	1492	4657
Old Numbers	1304	89	1569	5806	2632	19	1088	4115
PMU assigned	334	113	177	2597	30	427	895	875
Old Boxes	1597	31	1715	4784	2540	295	1732	4247
Literature Present	15	1	11	87	9	5	31	17
Missing Specimens	38	1	23	211	34	15	27	78
Red Dots for Types	136	102	205	3864	4	79	716	1071
Photos or Illustrations	15	1	10	34	3	2	19	26
Empty or Inaccessible	3	1	28	116	46	1	45	8

Table 5 - Conservation Review collections data as percentages of the totals, representing what proportion each collection represents in the total counts.

Conservation Review, Collections Data as Percentages of the Totals								
Criteria	**REF**	**OVS**	**PAL**	**INV**	**SKN**	**STN**	**MES**	**CEN**
Total Trays	8.2%	2.1%	11.6%	25.6%	10.7%	2.6%	15.8%	23.5%
Total Boxes	7.4%	0.9%	7.9%	38.1%	12.1%	2.0%	9.0%	22.6%
Plastic Protection	21.5%	0.0%	9.1%	16.2%	0.1%	5.9%	23.7%	23.5%
Needs Conservation	1.0%	0.1%	1.1%	34.6%	22.2%	5.5%	3.2%	32.3%
New Labels	13.7%	0.1%	6.8%	45.2%	0.1%	18.2%	15.4%	0.3%
Typed Labels	3.0%	0.1%	3.6%	80.6%	1.9%	0.0%	3.1%	7.7%
Handwritten/No Labels	7.7%	1.3%	9.3%	25.5%	16.6%	0.1%	9.6%	30.0%
Old Numbers	7.8%	0.5%	9.4%	34.9%	15.8%	0.1%	6.5%	24.8%
PMU assigned	6.1%	2.1%	3.2%	47.7%	0.6%	7.8%	16.4%	16.1%
Old Boxes	9.4%	0.2%	10.1%	28.2%	15.0%	1.7%	10.2%	25.1%
Literature Present	8.5%	0.6%	6.3%	49.4%	5.1%	2.8%	17.6%	9.7%
Missing Specimens	8.9%	0.2%	5.4%	49.4%	8.0%	3.5%	6.3%	18.3%
Red Dots for Types	2.2%	1.7%	3.3%	63.0%	0.1%	1.3%	11.7%	17.5%
Photos or Illustrations	13.6%	0.9%	9.1%	30.9%	2.7%	1.8%	17.3%	23.6%
Empty or Inaccessible	1.21%	0.40%	11.29%	46.77%	18.55%	0.40%	18.15%	3.23%

Table 6 - Conservation Review total counts by collection, representing the amount of counted material meeting each criterion.

Conservation Review, Percentages by Collection								
Criteria	**REF**	**OVS**	**PAL**	**INV**	**SKN**	**STN**	**MES**	**CEN**
Plastic Protection	94.1%	1.5%	37.4%	13.9%	0.2%	94.6%	85.6%	33.7%
Needs Conservation	0.5%	0.5%	0.6%	3.6%	7.3%	10.8%	1.4%	5.6%
New Labels	19.6%	1.0%	9.1%	12.6%	0.1%	95.5%	18.2%	0.2%
Typed Labels	7.8%	2.5%	8.6%	40.4%	3.0%	0.0%	6.6%	6.5%
Handwritten/No Labels	72.6%	96.5%	82.3%	47.1%	96.9%	4.5%	75.2%	93.3%
Old Numbers	79.6%	44.1%	89.9%	69.1%	98.9%	4.3%	54.9%	82.5%
PMU assigned	20.4%	55.9%	10.1%	30.9%	1.1%	95.7%	45.1%	17.5%
Old Boxes	97.5%	15.3%	98.2%	56.9%	95.4%	66.1%	87.3%	85.1%
Literature Present	10.4%	2.8%	5.4%	19.4%	4.8%	11.1%	11.2%	4.1%
Missing Specimens	2.3%	0.5%	1.3%	2.5%	1.3%	3.4%	1.4%	1.6%
Red Dots for Types	8.3%	50.5%	11.7%	46.0%	0.2%	17.7%	36.1%	21.5%
Photos or Illustrations	10.4%	2.8%	4.9%	7.6%	1.6%	4.4%	6.9%	6.3%
Empty or Inaccessible	2.08%	2.78%	13.79%	25.89%	24.60%	2.22%	16.30%	1.95%

Table 7 - Conservation Review Percentages by collection, representing the proportion of counted material meeting each criterion.

4. Discussion

4.1 Methodology

To begin, the robustness of the methodology explored in this work is assessed. The inventory was largely suitable for application in a large-scale museum context, providing a comprehensive set of criteria necessary to adequately document the geoheritage material (Figure 1). One additional category, Dimensions, was introduced to provide a concrete scale, as images—even those with a scale—can be misleading.

The primary challenge with the inventory was the variability in the quality and quantity of information available for individual items. As detailed in the results, 49.2% of items lacked associated age information, and 12.2% of items were missing acquisition or collector details. While such information can be retrieved by consulting the original publications linked to the material, ideally, well-preserved and curated collections at the Museum of Evolution should have this information, including the associated age, clearly indicated on the labels.

For the purpose of evaluating the strengths and limitations of the applied methodology, only information and literature readily accessible (e.g., in English and within the room) or directly accompanying the material were recorded. External sources were not actively sought due to limited time. This approach underscores the difficulties inherent in inventorying older and poorly conserved material and highlights the critical role of involving curators and other knowledgeable staff in the inventory process, as well as the importance of labels with publication data. Curatorial expertise in sub-collections and the history of individual items is invaluable and cannot be replicated by examining the material in isolation.

Next, valuation methodology is analysed. Several criteria and parameters within the valuation framework effectively capture the intricacies of collection items, such as 'Scientific Interest', 'State of Conservation', 'Diversity', and 'Accessibility'. Items generally scored low in 'Diversity' and 'Accessibility', reflecting their status generally as singular fossils accessible only by curator permission, rather than indicating a flaw in the parameters themselves.

However, certain aspects of the valuation process require adaptation to better account for the cultural significance of the material. Two categories, 'Traditional and Symbolic Use' and 'Industrial Use', went entirely unused in this evaluation. Although both are reasonable categories, the indicator parameters did not apply to any of the recorded material, resulting in the omission of significant cultural considerations. For example, collections or specimens may hold cultural value due to associations with notable collectors, donors, or authors, regardless of their traditional or industrial uses. Specimens described in the works of Wiman and Dalman are of considerable significance to the field of palaeontology, even if their scientific utility is limited at present, or if their state of conservation is poor. This cultural significance is poorly reflected by the existing criteria. To address this, it may be necessary to introduce an additional category for other cultural values, or to adapt the 'Traditional and Symbolic Use' category to include these considerations.

The category 'Degree of Scientific Knowledge' also presents challenges. This criterion assigns the highest score (4) to material 'Cited in theses and published studies in scientific periodicals of national relevance' (Table 2). However, publication in theses does not necessarily indicate the quality of a specimen, as many are not publicly accessible, making it difficult to verify such citations unless this information is explicitly provided with the material. Evidently, the inclusion of material in this work, as part of a methodological study, does not inherently increase its cultural value, especially as the focus is not on the material itself.

Additionally, there is room for bias in this category, as the interpretation of what constitutes an 'internationally relevant' publication can vary depending on the field and the date of publication. This is particularly problematic when evaluating the significance of older publications, where metrics like Impact Factor, which can change over time, may not accurately reflect their historical importance. Thus, although the age and frequency of publication of an item can contribute to its cultural value, this is not currently accounted for in any category.

'Rarity' is a valuable category for valuation, but it is difficult to assess accurately. In some cases, material may seem to be rare, but without the total digitisation and open access to a countries or regions collections, it may be impossible to determine the rarity of certain geological materials within a reasonable timeframe for conducting the inventory. This presents a significant challenge in accurately representing the value of understudied specimens, especially in countries with limited digitisation of geological material from ex-situ collections.

Similarly, the criterion 'Origin' can be difficult to ascertain due to the age of some collections. Many items have no country or locality assigned to them, making it impossible to determine their origins or how exhausted the locality is. Many items lack country or locality information, making it impossible to ascertain their origins or the depletion status of the locality. Additionally, some fossil localities, while not exhausted, are inaccessible to the public or researchers. For example, material from countries like Afghanistan or Myanmar may be of increased value due to its rarity in collections, even if the deposits themselves are not depleted. This situation is not well represented by the current methodology but could be easily adapted in future works.

'Fragility' is a robust category, yet it shares the same issue as 'Origin', where the evaluator needs extensive knowledge of numerous collection sites and must rely on locality information accompanying the material. It also does not account for material that, initially appearing well-preserved, faces or has faced preservation challenges post-extraction, such as pyrite fossils that are initially well-preserved but depend on stable conditions in collections or chemical treatments. Expanding this criterion to include such aspects of fragility would be beneficial.

'Specimen Size' is generally suitable for its purpose, although the terminology could be improved. The term 'Usual' could be replaced with 'Average' or 'Average range'. It can be challenging to discern if some material is larger or smaller than is typical, as fossils often have a size range, and deviations from the average is not necessarily significant or an indicator of increased value. Moreover, finding the average size of material can be difficult, with original descriptive literature often inaccessible or locked behind paywalls, presenting another challenge to accurate grading using this methodology. There is also no indicator of completeness, which could be encompassed by a reworked form of this criterion.

The criterion 'Interpretation Potential' is problematic. It is framed as grading a specimens' ability to express its 'geological importance and utility', but moreso relies on the public's knowledge of earth and natural sciences. Even highly significant fossils may seem uninteresting or redundant to a layperson unaware of their stratigraphical or morphological importance. This issue particularly affects invertebrate material, which can be extremely valuable to specialists but whose utility is often unknown to the public. For example, a high-quality palynological collection may appear less useful than a poorly conserved dinosaur bone to a layperson. However, with appropriate explanation, the practical uses of the palynological collection could be recognized as far more significant. Therefore, it seems unfair to rank fossils based on their ability to express 'geological importance and utility' when this relies heavily on accompanying educational material. Grading specimens in this way also results in a lower score for less recognisable material, further reducing the 'value' of the material.

'Awareness Raising Potential' is a good category in principle but requires a degree of subjectivity from the assessor. What one person considers part of the public imagination, another may view as niche and not easily recognized. This subjectivity negatively impacts the grading of invertebrate fossils, which may otherwise be of high value. Thus, if museums use this valuation ranking to assist in popularising their material, valuable invertebrate or micro- fossils may be overlooked, losing opportunities to keep them visible in the public eye. Future work should aim to reduce subjectivity in this criterion.

The first three parameters of 'Scientific Interest' are robust, but it should be noted that an item's designation as a Holotype or other 'type' does not necessarily increase its value significantly. Many Holotypes, especially those described in the 19th or early 20th centuries, are in poor condition and have little scientific value outside of being the first-described. Paratypes are also not included in this criterion as might be expected. Therefore, this category should be adapted to include Paratypes and better represent the most valuable material, possibly combining the parameters for the grades of 2 and 4 for a maximum grade.

As discussed in the methodology, the weighting of values is generally considered suitable, although this remains a topic of debate within the broader Geoheritage & Geoconservation community (da Silva, Mansur, and de Costa, 2023). Future adaptations and new methodological proposals may benefit from experimenting with the weightings and arguing for the advantages of specific configurations. The mathematical calculations, however, required significant revision to accurately represent the desired data and trends. The results also benefited from normalisation to 100, which should be standard practice in any methodology aimed at increasing accessibility and promoting collaboration between geoscientists and museum specialists. Assuming the revised equations are correct, they would be suitable for use in future methodologies.

The conservation review criteria were specifically adapted to meet the resource needs of the museum collections. They effectively addressed all the key aspects of the individualised conservation targets within the museum, and should not be considered as a suggestion of a conservation review method suitable for all natural history museums.

Regarding RStudio, various configurations of the data could be explored for statistical analysis using inventory, valuation, and conservation data. Therefore, the code used in this methodology (Appendix I) is not particularly significant. It is only indicative of the types of information that can be extracted from the data, and is adaptable for any style of analysis.

4.2 Inventory and Valuation Results

As shown in Figure 7, the Values for Collection results are relatively low. The highest-scoring item achieved 34.2 out of 100, missing nearly two-thirds of the available points. The mode falls within a score range of 14.9

to 17.1, encompassing 129 items, which is less than one-fifth of the total points (Figure 7). This suggests that the vast majority of items in the inventory possess low collection value. However, it is important to note that the heritage value of these materials is underrepresented, as discussed earlier, with no weightings assigned to account for factors such as age, collector, author, or historical significance—despite the substantial value these attributes confer on collection pieces. This lack of consideration may have skewed the results, underestimating the true value of many items.

Figure 8 presents a more balanced distribution of grades for Values for Popularisation, with the highest score at 78.8 out of 100. The mode for this category is between 27.5 and 32.5, which, although still less than half of the total possible score, is almost double the mode for Value for Collections. However, this mode is less pronounced, with a broader and more even distribution of scores across other nodes within this category (Figure 8). These results demonstrate that the inventoried material generally ranks higher in Popularisation Value than in Collections Value, however the items' Collections Value is more spread across all grades.

Figure 9 also highlights the inventory items ranked highest and lowest for each value. Among the top five items, two out of the five highest-ranked for Collections Value also fall within the top 10% of Popularisation rankings (highlighted in blue), while three out of the top five for Popularisation Value are within the top 10% of Collections rankings (highlighted in orange) (Figure 9). This indicates that half of these top items are highly valued in both categories, making them broadly valuable to the museum for both collection and popularisation purposes. A similar trend is observed among the lowest-ranked items: two of the four items tied for the lowest Collections Value are also the two lowest-ranked in Popularisation Value, indicating that the poorest performing items generally score low grades in both areas (Figure 9). This correlation is expected, given that the five valuation categories are shared between Collections and Popularisation criteria and cultural value is poorly accounted for (Table 1, Table 2). Thus, items performing poorly in these categories would need to excel in the non-overlapping values to rank highly in either category. However, as Figures 9 illustrates, just over half of the items follow this scoring trend, so it cannot be conclusively stated that the highest- and lowest-scoring items are universally valuable or worthless across both categories. Nonetheless, ranking data in this way can inform the selection of the best items for new exhibitions, outreach programmes, research, and publication, by providing a comprehensive overview of their potential utility.

The RStudio rankings demonstrate the general quality of different categories in the collection (Figure 10). Only 6% of the inventoried items performed highly in both Collections Value and Popularisation Value, while just over half that number (3.35%) appear in the bottom 10% for both values. There is no overlap between the items in the bottom 10% of one category and the top 10% of the other, indicating that the highest- and lowest-scoring items tend to excel in one category only (Appendix II). This distinct separation suggests that the attributes that contribute to high performance in one valuation do not necessarily correlate with success in the other, highlighting the importance of diverse and separate criteria in evaluating museum collections.

Belemnites consistently perform poorly in both valuations, receiving the lowest average scores, highlighting a weakness in the collections (Figure 10a, 10b). This suggests that future acquisition and curation efforts should focus on improving the Belemnite collections in the museum. Trilobites, on the other hand, show mixed levels of quality. They rank highest in the number of items in the top 10% for Collections Value and second in the top 10% for Popularisation Value, but they are also first place for the number of items in the bottom 10% in both valuations (Figure 10c, 10d, 10e, 10f). This discrepancy is likely due to the presence of many partial, small, and damaged Trilobites, as well as casts with poor detail. To improve the ranking of Trilobites, the inventory could be improved to better account for heritage value in relation to their collector and publisher. Currently, this aspect is not adequately represented, leading to a ranking of 14th and 15th place in average Collections and Popularisation Value, respectively (Figure 10a, 10b).

The results are somewhat biased due to the unequal representation of each item type in the inventory. This is particularly evident with 'Fish', which ranks first in the average Popularisation scores, a ranking based on only one specimen (Figure 10b). This bias could be mitigated by expanding the inventory to include all specimens in the museum, as would be the goal of a thorough inventory. Nevertheless, valuable insights can be made from analysing any inventory category and any aspect of the valuation data, providing innumerable configurations for analysis. This demonstrates the potential for inventories and valuations to significantly benefit and guide museum work and acquisition strategies.

4.3 Conservation Review Results

When analysing the collections in relation to the overall totals, it would be expected that the largest and smallest collections to correspond to the largest and smallest percentages across each category. For example, given that the Invertebrate Type collections comprise the highest number of boxes and trays, at 38.1% and 25.6% respectively, it is reasonable to expect that they would also account for the highest percentage of occurrences in each category (Table 6). This expectation is largely reflected by the results; the Invertebrate

Type collections indeed represent the highest percentages across all categories, with the exception of the Mesozoic collection, which accounts for 23.7% of all instances of Plastic Protection within the collections (Table 6). Accordingly, the Oversized collections represent the lowest proportion of incidences in all categories except for *PMU* Numbers and Red Dots for Types, where the Skanian collections have even lower occurrences (0.1%) (Table 6).

Therefore, the more interesting data are the outliers, as they represent deviations from the expected trends. For example, the Cenozoic collection represents a disproportionately low number of *New Labels* and *Typed Labels* (0.3% and 7.7% respectively) (Table 6), and the highest percentage of No/Handwritten Labels (30%), These findings suggest that future conservation efforts can be directed towards increasing the number of new labels in this collection. The Reference collection, on the other hand, has a higher percentage of Plastic Protection than other collections and a lower percentage of Conservation Needs relative to its size (Table 6). This data indicates that conservation efforts have been undertaken to improve this collection. Similarly, the Sternberg collection has a high proportion of *New Labels* and *PMU*s relative to its size, suggesting that significant effort has been invested in the labelling and cataloguing of this material (Table 6).

Further breakdown of the review data by collection reveals areas where conservation efforts have either succeeded or require improvement. In some instances, the results are a product of targeted conservation work (Jan Ove Ebbestad, personal communication, 4th August 2024) or due to the nature of the items themselves. For example, the Oversized collection contain the lowest percentage of old boxes and minimal conservation needs - 15.3% and 0.5% respectively (Table 7). This is likely due to the nature of the collection, which includes large items such as moulds, replicas, and fossils in plaster casts, rendering them less susceptible to damage compared to more fragile specimens. Consequently, these items are not required to be stored in new boxes and generally remain in good condition. However, this collection has a high proportion of items without labels, or with only handwritten labels (96.5%) (Table 7). This result is heavily influenced by the Grey Whale (*Eschrichtius robustus*) specimen, being fully catalogued with *PMU*s assigned but lacking labels (Table 7).

The Reference Collection has a high percentage of Plastic Protection, at 94.1% of all boxes containing protected labels, and ranks amongst the lowest in terms of conservation needs (0.5%) (Table 7). This collection contains some of the museum's most valuable vertebrate type specimens, many of which have undergone extensive conservation before being loaned or published. Given the high amount of published material in the Reference Collection, it is expected to have a relatively high number of missing items from loans (2.3%). However, the relatively low percentage of Red Dots for Types (8.3%) suggests that further work is needed to mark type specimens more clearly. Like most collections, it has a high percentage of Old Numbers (79.6%), which represents a key focus area for future conservation efforts (Table 7). Although photos and illustrations are occasionally present in the boxes or trays, they represent less than 10% of the total across all collections, except in the Reference Collection (10.4%) (Table 7).

In the Palaeozoic collection, relatively few items need conservation (0.6%); however, it generally has a poor overall conservation status. Only 34.7% of the items have Plastic Protection, and 87.6% of the labels are Typed or No/Handwritten Labels. Only 10.1% of items have a *PMU* assigned, and 98.9% of items are in old boxes, suggesting that significant work is needed in this collection to meet modern conservation standards. The majority of boxes in the collection have metal fixings on the corners, which, while generally adequate, pose a risk of rusting due to variable temperature and humidity in the storage rooms. This can lead to the separation of the corners of boxes containing heavy items. Given these risks, it is advisable that the Palaeozoic collection be prioritized for upgrading to modern boxes during future conservation efforts. The modern boxes for new acquisitions are standardised to save space, but they are also thicker, higher, and more robust than the old boxes.

The Invertebrate Type Collection holds some of the oldest and newest material, resulting in mixed conservation results. While 13.9% of items have Plastic Protection, the majority of items have Old Numbers (69.1%). However, the collection has a high proportion of Red Dots for Types (46%) and Literature Present in the trays (19.4%) (Table 7). Ideally, each tray or set of trays containing a sub-collection should include literature relating to the samples, but 99.20% of trays have no literature, book, or other material concerning publication or research (Table 6). In some cases, this is because the material is unpublished or the literature is consolidated in a single location, such as the Invertebrate Type and Reference Collection rooms, where literature is also stored on shelves. Considering this, the actual proportion of literature present is higher than the 19.4% recorded in the trays (Table 7). Compared to other collections, the Invertebrate Type Collection ranks moderately high in conservation needs (3.6%) and missing specimens (2.5%). All collections contain fewer than 9% *Typed Labels*, except for this collection, which has 40.4%, more than four times the highest percentage in other collections (Table 7). Conservation work could be directed towards introducing *New Labels* (12.6%) and adding Plastic Protection to improve the collection’s statistics in this area (Table 7).

The Skanian collection is poorly conserved, performing poorly across all categories except for missing specimens, which are relatively few (1.3%). It has high percentages of Conservation Needs (7.3%), Old Numbers (98.8%), and Old Boxes (95.4%), along with low percentages of *New Labels* (0.1%) and Plastic Protection (0.2%) (Table 7). This makes it one of the worst conserved areas in the collection, requiring substantial work and resources to bring it up to museum standards

The Sternberg Collection displays an unusual mix of conservation results. It has the highest percentage of *New Labels* (92.5%), *PMU*s (95.7%), and Plastic Protection of any collection (94.6%), suggesting that a high degree of conservation efforts have been made here (Table 7). Despite this, it also has the highest number of missing specimens (3.4%) and the greatest need for conservation of any collection (10.8%) (Table 7). This indicates that the collection is a work in progress. Although it has the highest percentage of missing specimens of any collection, this is largely attributable to items currently on display in the exhibitions. The Invertebrate Type Collection has the greatest number of missing items, with 211 individuals, representing 2.51% of the total (Table 7). While some of these are out on loan, there are more instances of empty boxes in this collection than in the Sternberg Collections, highlighting a key area for future recovery efforts.

The Mesozoic collection is average compared to other collections, with most categories showing middling values. The exception is Plastic Protection, which covers the majority of items (85.6%) (Table 7). The collection requires relatively little conservation (1.4%), and just under half of the items have *PMU*s assigned (45.1%). However, the majority of items are stored in Old Boxes (87.3%) and have No/Handwritten Labels (75.2%) (Table 7). This collection would benefit from targeted conservation efforts across all areas, though it is not as poorly conserved as the Sternberg Collection.

The Cenozoic Collection, the second-largest in the museum, also exhibits complex conservation results. It has an extremely low number of *New Labels* (0.2%), and only 17.5% of items have *PMU*s assigned (Table 7). Although the collection has a low proportion of Literature Present (4.1%), it also has relatively few empty or inaccessible trays (1.95%). The collection exhibits average levels of Plastic Protection (33.7%) and Old Boxes (85.1%), indicating that conservation efforts should focus on creating new labels and replacing old boxes where feasible (Table 7).

5. Conclusions

5.1 Methodology

The depth of information that can be obtained from a quantitative and qualitative analysis of a museum's collection is immense, offering invaluable opportunities for museums to gain insight into both their overall collections and the individual objects within them. Utilizing statistical methods with inventory and valuation data can provide a range of functions, from guiding conservation work and research, to informing future acquisitions, educational outreach, and exhibitions. This data not only supports daily museum operations but also can play an administrative role in campaigns for resources and funding. It offers concrete numbers for reports and helps demonstrate to stakeholders the content of collections and their conservation status.

The success of such inventories may be diminished if conducted by external personnel, underscoring the need for museum staff to engage with geoheritage initiatives and carry out inventories and valuations using a standardised methodology. Since many museums already employ similar processes for inventory management, only minimal adjustments should be needed to align current practices with the methodology discussed in this study. In some cases, no changes might be necessary at all to still achieve the desired outcome.

Beyond the intra-museum benefits, the data can facilitate inter-museum collaboration on scientific, educational, and cultural projects. The inventory and valuation structures outlined in this work are easily replicable and can be integrated into broader networks, enabling standardised and accessible digitisation of geological material. With the development of a more inclusive valuation methodology, this database format can simplify research within and across institutions by adopting standardised formats for data handling. Given the extent of the data which can be extrapolated from a completed valuation, the application of ex-situ Geoheritage valuation techniques within museums is extremely worthwhile as an additional device in the curators toolkit.

While the time required to reformat and update existing catalogues to match the inventory outlined in this research may be a barrier for some museums, those with similar existing inventories have a significant opportunity to integrate valuation metrics into their ongoing catalogues and evaluations. This integration could occur alongside regular conservation activities, either by the curators themselves or through the assistance of visiting experts. The valuation data collected in this study has already revealed numerous insights about the Museum of Evolution's collections, underscoring the value of continuing this methodology for future conservation, acquisition, and research purposes. Conducting conservation reviews alongside valuations can help to highlight issues when determining the value of an item and how widespread an issue is in the collection.

5.2 Data

The valuation and conservation assessment conducted on the Museum of Evolution provides detailed reports on the strengths and weaknesses of the collections. This analysis demonstrates past conservation efforts, highlights unique aspects of the collection, and points out where future conservation efforts would be most beneficial. The valuation data shows which fossil groups are more valued for collections or popularisation and using this data will benefit the museum greatly, helping to guide acquisitions, exhibitions, educational events, and conservation work. In time, the data may also serve as a foundation for future funding campaigns. No area of the collections are complete, and each require varying work in order to meet the museums conservation standards. Notably, the Skanian and Palaeozoic collections are among the least conserved, indicating that they should be targeted in future conservation works. Across the collection, there are high instances of old inventory numbers and no/handwritten labels, which reduce the accessibility and usability, especially for visiting researchers. Addressing these labelling issues should be a key focus for the museum's efforts to bring its collections up to modern standards.

The analysis revealed particularly interesting trends within specific fossil groups. Trilobites, for example, exhibit both high and low valuation scores, suggesting that parts of this collection may be suitable for disposal in the event of rehoming or low resource availability. Belemnites consistently showed poor scores, indicating a potential focus area for future acquisitions. Further statistical analysis of the existing data will allow for the identification of further trends in the material, and subsequent inventories will expand these insights on a wider scale. Overall, this study demonstrates the significant benefits of applying geoheritage and geoconservation inventory and valuation techniques to a large-scale museum setting. Future efforts should explore the potential for these methodologies to be applied in a variety of contexts, both within and outside of museum collections, to validate their utility and test their applicability.

5.3 Future Directions

Future research should prioritise refining and further developing the methodologies outlined in this work. While the criteria for the inventory process are largely effective and adaptable, the valuation criteria require extensive revision to better serve the complexity of geological materials found in museum collections. Currently, these criteria do not fully account for the diversity of heritage values associated with different types of geological specimens in museum collections.

The study primarily focused on palaeontological samples, with limited coverage of sedimentary and mineralogical specimens. Therefore, future research would benefit from applying the inventory and valuation methodologies to a broader range of geological materials across various institutions. Given the relative infancy of ex-situ geoheritage methodologies, there is considerable potential for new approaches to emerge, building on the insights from this work and previous studies.

The weighting proposed in the methodology was not examined closely in this work, however it is flexible so future methodologies may wish to explore how adjusting the criteria might impact the overall evaluation. The original equations used in the valuation methodology were somewhat lacking for non-geoscientist application. Future efforts may focus on refining these equations or developing entirely new ones.

The litany of intra-museum benefits to conducting a valuation are evident, as are the opportunities for collaboration between museums on scientific, educational, cultural, and aesthetic projects involving geological materials. Once a more widely accepted valuation method is developed, discussions with museum professionals can pave the way for larger ex-situ geoheritage initiatives beyond the scope of museum collections.

Looking to international initiatives, the UNESCO Global Geoparks program has been successful in documenting and preserving some of the world's most significant geological sites, with a focus on geoheritage, geodiversity, and research. Although ex-situ geoheritage is generally regarded within the realm of museums, future projects could extend these efforts to a broader geological context. Following the works of the World Heritage site catalogue and the UNESCO Global Geoparks programme, there is potential to create a global inventory of the most important ex-situ geological material, representative of a geological framework spanning across geological time and environments. This initiative, similar to the UNESCO Memory of the World (MoW) Register, would be aimed at documenting and preserving ex-situ geological heritage of global significance, particularly in areas under threat, in order to make it globally accessible, raise public awareness, and promote research. Similar inventory and valuation methodologies to the one described in this work could serve as a foundation for global initiatives.

References

ASGMI (2018) Metodología de valoración del patrimonio geológico. 1er Taller de Patrimonio de la ASGMI.

Brilha, J. (2016). Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: A Review. *Geoheritage*, *8*(2), 119–134. https://doi.org/10.1007/s12371-014-0139-3

Brilha, J. (2018). Geoheritage. In *Geoheritage* (pp. 69–85). Elsevier. https://doi.org/10.1016/B978-0-12-809531-7.00004-6

Brilha, J. and Reynard, E. (2018). Geoheritage and Geoconservation: The Challenges. In *Geoheritage* (pp. 433-438). Elsevier. https://doi-org.ressources-electroniques.univ-lille.fr/10.1016/B978-0-12-809531-7.00025-3

Bruno, D. E., Crowley, B. E., Gutak, J. M., Moroni, A., Nazarenko, O. V., Oheim, K. B., Ruban, D. A., Tiess, G., & Zorina, S. O. (2014). Palaeogeography as geological heritage: Developing geosite classification. *Earth-Science Reviews*, *138*, 300–312. https://doi.org/10.1016/j.earscirev.2014.06.005

Da Silva, R. G. P., Mansur, K. L., & De Castro, A. S. (2023). Methodological Proposal for Inventory and Quantitative Valuation of Ex Situ Geological Heritage, a Case Study at the Museu da Geodiversidade (MGeo/IGEO/UFRJ). *Geoheritage*, *15*(2), 46. https://doi.org/10.1007/s12371-023-00812-1

De Lima, J. T. M., & De Souza Carvalho, I. (2020). Geological or Cultural Heritage? The Ex Situ Scientific Collections as a Remnant of Nature and Culture. *Geoheritage*, *12*(1), 3. https://doi.org/10.1007/s12371-020-00448-5

De Wever, P. and Guiraud, M. (2018). Geoheritage and Museums. In *Geoheritage* (pp. 129-145). Elsevier. https://doi-org.ressources-electroniques.univ-lille.fr/10.1016/B978-0-12-809531-7.00007-1

Endere, M. L., and Prado, J. L. (2015). Characterization and Valuation of Palaeontological Heritage: A Perspective from Argentina. *Geoheritage, 7,* 137–145. https://doi.org/10.1007/s12371-014-0124-x

Ferrez, H. D. (1994) Documentação museológica: teoria para uma boa prática. IV Fórum de Museus do Nordeste. Recife: 1991

Fidalgo, D., Fernández-Martínez, E. (2021). Should Neglected Fossils Be Considered as Geoheritage? The Case of Cenozoic Vertebrates Found in the Province of León (Spain). *Geoheritage, (13)*67. https://doi.org/10.1007/s12371-021-00589-1

Geert, F. V. (2022). The Exhibition of Geoheritage in Geoparks and Geological Museums. *Museologia e Patrimônio*, 164–183. https://doi.org/10.52192/1984-3917.2022v15n1p164-183

Haag, N. A., and Henriques, M. H. (2016). The Palaeontological Heritage of the Acre (Amazonia, Brazil): Contribution Towards a National Palaeontological Database. *Geoheritage*, *8*(4), 381–391. https://doi.org/10.1007/s12371-015-0163-y

Henriques, M. H., and Pena Dos Reis, R. (2015). Framing the Palaeontological Heritage Within the Geological Heritage: An Integrative Vision. *Geoheritage*, *7*(3), 249–259. https://doi.org/10.1007/s12371-014-0141-9

Henriques, M. H., Dos Reis, R. P., Brilha, J., & Mota, T. (2011). Geoconservation as an Emerging Geoscience. *Geoheritage*, *3*(2), 117–128. https://doi.org/10.1007/s12371-011-0039-8

Page, K. N. (2018). Fossils, Heritage and Conservation: Managing Demands on a Precious Resource. In *Geoheritage* (pp. 107-128). Elsevier. https://doi-org.ressources-electroniques.univ-lille.fr/10.1016/B978-0-12-809531-7.00006-X

Pena Dos Reis, R., and Henriques, M. H. (2009). Approaching an Integrated Qualification and Evaluation System for Geological Heritage. *Geoheritage*, *1*(1), 1–10. https://doi.org/10.1007/s12371-009-0002-0

Pereira, D. I., Pereira, P., Brilha, J., and Santos, L. (2013). Geodiversity Assessment of Paraná State (Brazil): An Innovative Approach. Environmental Management, 52(3), 541–552. https://doi.org/10.1007/s00267-013-0100-2

Ponciano, L., Castro, A., Machado, D., Fonseca, V., Kunzler, J. (2011). Patrimônio geológico-palaeontológico in situ e ex situ: definições, vantagens, desvantagens e estratégias de conservação. In: *Carvalho, I., Srivastava, N.; Strohchoen Jr., O; Lana, C. (Org.) (eds) Palaeontologia: Cenários de vida.* (*4*)1a, 853–869. Rio de Janeiro: Interciência.

Prosser, C. D. (2013). Our rich and varied geoconservation portfolio: The foundation for the future. *Proceedings of the Geologists' Association*, *124*(4), 568–580. https://doi.org/10.1016/j.pgeola.2012.06.001

Reynard, E. and Brilha, J. (2018). Geoheritage: A Multidisciplinary and Applied Research Topic. In *Geoheritage* (pp. 3-9). Elsevier. https://doi-org.ressources-electroniques.univ-lille.fr/10.1016/B978-0-12-809531-7.00030-7

Thomas, M. F. (2012). Geodiversity and Landscape Sensitivity: A Geomorphological Perspective. *Scottish Geographical Journal*, *128*(3–4), 195–210. https://doi-org.ressources-electroniques.univ-lille.fr/10.1080/14702541.2012.725863

Van Geert, F. (2019). In situ interpretation and ex situ museum display of geology. New opportunities for a geoheritage based dialogue? *International Journal of Geoheritage and Parks*, *7*(3), 129–144. https://doi.org/10.1016/j.ijgeop.2019.05.001

Appendices

Appendix I – RStudio Code

```
colpop <- read.csv("pathway > colpop.csv")
X <- colpop$Coll
Y <- colpop$Pop

bottom_10_coll <- order(X)[1:(0.1 * length(X))]
bottom_10_pop <- order(Y)[1:(0.1 * length(Y))]
overlap_bottom <- intersect(bottom_10_coll, bottom_10_pop)
length(overlap_bottom)

top_10_coll <- order(X, decreasing = TRUE)[1:(0.1 * length(X))]
top_10_pop <- order(Y, decreasing = TRUE)[1:(0.1 * length(Y))]
overlap_top <- intersect(top_10_coll, top_10_pop)
length(overlap_top)

bottom_coll_top_pop <- intersect(bottom_10_coll, top_10_pop)
top_coll_bottom_pop <- intersect(top_10_coll, bottom_10_pop)
length(bottom_coll_top_pop)
length(top_coll_bottom_pop)


colpop <- read.csv("pathway > colpop.csv")
coms <- colpop$coms
cols <- colpop$cols
pops <- colpop$pops


# Load necessary library
if (!require(dplyr)) install.packages("dplyr", dependencies=TRUE)
library(dplyr)
```

```r
# Check if cols, pops, and coms datasets exist in the environment
if (!exists("cols")) stop("Dataset 'cols' not found in the environment.")
if (!exists("pops")) stop("Dataset 'pops' not found in the environment.")
if (!exists("coms")) stop("Dataset 'coms' not found in the environment.")

# Ensure that all datasets have the correct length
if (length(cols) != 417) stop("Dataset 'cols' does not have 417 elements.")
if (length(pops) != 417) stop("Dataset 'pops' does not have 417 elements.")
if (length(coms) != 417) stop("Dataset 'coms' does not have 417 elements.")

# Combine the datasets into a data frame
data <- data.frame(cols, pops, coms)

# Function to calculate rankings based on average score
rank_by_avg <- function(dataset, category_var, score_var) {
  dataset %>%
    group_by(!!sym(category_var)) %>%
    summarise(avg_score = mean(!!sym(score_var), na.rm = TRUE)) %>%
    arrange(desc(avg_score))
}

# Calculate rankings based on average scores
rank_avg_cols <- rank_by_avg(data, "coms", "cols")
rank_avg_pops <- rank_by_avg(data, "coms", "pops")

# Function to calculate rankings based on the count of top 10% datapoints
rank_by_top_10 <- function(dataset, category_var, score_var) {
  threshold <- quantile(dataset[[score_var]], 0.9, na.rm = TRUE)
  dataset %>%
    filter(!!sym(score_var) >= threshold) %>%
    group_by(!!sym(category_var)) %>%
    summarise(count_top_10 = n()) %>%
    arrange(desc(count_top_10))
}
```

```r
# Calculate rankings based on top 10% datapoints
rank_top_10_cols <- rank_by_top_10(data, "coms", "cols")
rank_top_10_pops <- rank_by_top_10(data, "coms", "pops")

# Function to calculate rankings based on the count of bottom 10% datapoints
rank_by_bottom_10 <- function(dataset, category_var, score_var) {
  threshold <- quantile(dataset[[score_var]], 0.1, na.rm = TRUE)

  # Debugging: Check threshold value
  cat("Bottom 10% threshold for", score_var, ":", threshold, "\n")

  result <- dataset %>%
    filter(!!sym(score_var) <= threshold) %>%
    group_by(!!sym(category_var)) %>%
    summarise(count_bottom_10 = n()) %>%
    arrange(count_bottom_10) # Ascending order, lower is better

  # Debugging: Check if result is empty
  if (nrow(result) == 0) {
    cat("No data found in the bottom 10% for", score_var, "\n")
  }

  return(result)
}

# Calculate rankings based on bottom 10% datapoints
rank_bottom_10_cols <- rank_by_bottom_10(data, "coms", "cols")
rank_bottom_10_pops <- rank_by_bottom_10(data, "coms", "pops")

# Output results
cat("Ranking of coms categories by average cols scores:\n")
print(rank_avg_cols)
cat("\nRanking of coms categories by average pops scores:\n")
print(rank_avg_pops)
```

```
cat("\nRanking of coms categories by top 10% cols scores:\n")
print(rank_top_10_cols)
cat("\nRanking of coms categories by top 10% pops scores:\n")
print(rank_top_10_pops)

cat("\nRanking of coms categories by bottom 10% cols scores:\n")
print(rank_bottom_10_cols)
cat("\nRanking of coms categories by bottom 10% pops scores:\n")
print(rank_bottom_10_pops)
```

Appendix II – Data Workbook containing Images, Conservation Assessment, Inventory, Valuation Grades, and RStudio Results. https://zenodo.org/records/13735679