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Digitization of the Marine Herbarium "TAR" to Increase Biodiversity Knowledge

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Abstract

Over the past twenty years, significant efforts have been made to digitize natural collections. This process represents a crucial step in preserving and enhancing biodiversity data. In this context, the phycology team from the Institute for Water Research (CNR-IRSA) in Taranto (southern Italy), as a partner of the NRRP Project ITINERIS, and within the nascent European Research Infrastructure "Distributed System of Scientific Collections" (DiSSCo), answered to the challenge of digitizing and sharing the extensive biodiversity data preserved in the marine macrophyte collection Herbarium TAR. This herbarium includes over 500 species collected between 1982 and 2025. Digitization was carried out in accordance with international standards for imaging and in compliance with FAIR principles for metadata curation. A total of 353 digital specimens were produced, including 152 species of seaweeds (76 Rhodophyta, 47 Heterokontophyta, and 29 Chlorophyta) and 3 species of Tracheophyta. Notably, 15 non-indigenous species were documented. Part of the metadata, structured using the Darwin Core standard, has been published on GBIF. This initiative, carried out within the ITINERIS framework, highlights the value of both long-term biodiversity monitoring and digital data in supporting research on climate change, biological invasions, and the conservation of marine ecosystems.

Keywords: digital resources; DiSSCo; FAIR principles; GBIF; ITINERIS; Natural Science Collections; seaweeds

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1. Introduction

Over the past twenty years, efforts have been made to digitize natural collections through databasing and imaging projects to make specimen data available. Natural science collections (NSCs) represent essential research tools and a potential source of data for biodiversity studies and conservation actions [1]. They are the repositories of vital reference specimens and provide useful information about species distribution and ecology [2], against which modern observations and collections can be compared, but they are also very useful to obtain information on species phenology, phylogeny, and taxonomy [3–5]. Moreover, they are important for ecological studies aiming to understand the long-term effects of environmental alterations due to pollution and/or climate change and can represent the basis for taxonomic studies and understanding of the life cycle of species [6–11].

Among NSCs, herbaria represent a collection of catalogued plant samples, often pressed and dried on paper sheets, with associated information, preserved for different purposes. According to Thiers [12], there are about 4000 herbaria collections worldwide. Starting from the early 2000's, the first projects for the creation of digital repositories,

aiming to share images of this natural heritage, were initiated [13–17]. One of the main benefits of digitization is preserving the physical sample from potential damage caused by handling and transport, as well as reducing the relative costs arising from these operations [18]. Moreover, thanks to new technologies, other advantages include greater accessibility, searchability, promotion of collaboration among researchers, and integration with other collections or observations [19–22]. Digitization of a natural collection is the crucial first step in transforming data connected to physical specimens into digitally accessible representations [23]. This process can occur at varying levels, depending on the purpose, available technology, resources, and budget constraints [24,25]. To date, the digitization of herbaria has become an essential step in ensuring the contemporary relevance and functionality of natural collections in an increasingly digital socio-economic landscape [26].

Currently, there is a considerable variability in the extent to which specimen data are potentially acquired, both within individual collections and across institutions [27]. To address this inconsistency and make possible the re-use and interoperability of data, the Minimum Information about a Digital Specimen (MIDS) specifications have been developed [28]. This is a standard including the minimum information required to improve discoverability, research use, and cross-linking of data. This provides a structured framework for assessing the completeness of transcribed specimen data and the availability of associated media files, supporting a standardized and consistent methodology for quantifying the level of digitization of specimens within a collection. Four levels have been defined between 0 and 3, each representing a more complete and interconnected digital representation of the specimen. Level 0 (bare) establishes a basic link between the physical specimen and its digital representation, providing a unique identifier and allowing for further information to be attached. Level 1 (basic) adds at level 0 higher-level taxonomic and geographic information (e.g., family and country). Level 2 (regular) adds data about collection locality, collector, and date. Level 3 (extended) adds external data not directly retrievable by the label (e.g., bibliographic references, data sets) [29]. The MIDS can differ based on whether the stored specimen is a land or aquatic plant or a macroalga. Even within species, the MIDS can vary. For example, a seaweed specimen's information may include the benthic zone where it was found (e.g., littoral or sublittoral), its habitus (e.g., attached or floating), and its life stage (e.g., gametophyte or sporophyte).

After digitization, the publication of data in a searchable database, such as the bioinformatic portal Global Biodiversity Information Facility (GBIF; www.gbif.org accessed on 11 March 2025), is another important step of the entire process, ensuring compliance with the FAIR principles, namely, Findable, Accessible, Interoperable, and Reusable [30]. GBIF is a worldwide collaboration and data platform that manages the Global Registry of Scientific Collections (GRSciColl) and ensures open availability of biodiversity information to aid scientific research, inform policy, and guide decision making [31]. Through this platform, researchers worldwide can access collections remotely to carry out the analysis of broad biogeographic and cross-taxa patterns [5,32–35].

In this context, the nascent European Research Infrastructure "Distributed System of Scientific Collections" (DiSSCo—www.dissco.eu) has its primary goal in the digital integration, harmonization, and unification of all European NSCs, creating a comprehensive and accessible knowledge base for research and other purposes, that is a "digital twin" of physical specimens, making them accessible through a unified digital platform. DiSSCo will ensure all data adhere to the FAIR principles [36]. To this end, the Italian network of NSCs hosted at the natural history museums, botanical gardens, and research institutes across Italy, which will become one of the nodes of DiSSCo, has accomplished the collection digitization within the framework of the NRRP Project "Italian Integrated Environmental Research Infrastructures System"-ITINERIS (https://itineris.cnr.it). The marine macro-

phyte collection TAR, stored at the Institute for Water Research (CNR-IRSA), formerly Istituto Talassografico "A. Cerruti" of Taranto, was one of the collections involved in this project. A high-quality, digitized seaweed collection offers scientists an essential tool for studying various aspects of marine biology, such as ecology, biodiversity, invasive species, and the effects of global climate change [37]. Recently, at the University of California in Santa Barbara, a collaborative project has been launched, which aims to build a growing data set with several seaweed herbaria, useful to deal with inquiries concerning climate change, ocean currents, invasive species, and biodiversity on the Pacific Coast of North America [38]. Until now, only a few European seaweed herbaria have been digitized and made available online [37].

Here, we report the results of the digitization process of the marine Herbarium TAR, which allowed the creation of a digital repository of seaweeds and phanerogams collected over forty years, mainly along the coasts of the Mar Grande and Mar Piccolo of Taranto (Ionian Sea, southern Italy), but also in other Italian localities and abroad. Moreover, the possible indication about the usefulness of this NSC in the study of biodiversity change is highlighted.

2. Materials and Methods

The Herbarium of the Istituto Talassografico "A. Cerruti" of Taranto (CNR) TAR (https://sweetgum.nybg.org/science/ih/herbarium-list/?NamOrganisationAcronym=tar accessed on 30 January 2025) preserves marine macrophytes, mainly collected from the Taranto seas and identified during floristic and ecological studies, performed within the framework of various institutional activities and financed projects that allowed the long-term study of the biodiversity of the investigated areas. It can be considered a young herbarium, since the first collected specimens date back to 1982, and it is continuously updated.

The physical objects of the herbarium occur in dried and pressed form, mounted on a paper sheet (*exsiccata*), and preserved in a protective cover. These herbarium sheets are stored in five cabinets divided according to the different species' phylum. Two dressers include all Rhodophyta species, other two include the Heterokontophyta, and the last one includes the Chlorophyta sheets, except for one drawer containing a few Tracheophyta samples.

The digitization and metadata acquisition of the Herbarium TAR started at the end of February 2024 and finished in mid-June 2024. The digitization process followed different steps: specimen selection, pre-digitization curation (i.e., cleaning, mounting), sample labelling, acquisition of a high-resolution digital image, databasing and data enhancement, publishing, and archiving. To avoid damage, each sheet is taken and handled with cotton gloves to apply a label with an alphanumeric ID code, called "Specimen ID", including the Herbarium code and a progressive number (e.g., TAR-000001). This code has also been used for naming the scanned sample. Afterwards, a second label has been applied on each sheet, containing the scientific name of the species, the date and place of collection, the name of the person who collected it (*legit*), and the name of the person who identified the species (*determinavit*). For each species, the correctness of the scientific name has been checked, and, when necessary, the nomenclatural update has been performed according to Algaebase (https://www.algaebase.org/).

After the specimens were organized and nomenclatural verifications were complete, when possible, before imaging, attention was paid to several important steps. In particular, the presence of all key elements, i.e., principal label, ID, color reference chart, and supplementary labels. In case of dirt or dust, it was carefully removed with the specially provided tools (brush and microfiber napkin).

Concerning image acquisition, each herbarium sheet was scanned using a customized Planetary Scanner unit (BUCAP, Bookeye 5 V2, Monterotondo Scalo, Italy) consisting of a

CCD scanner camera and an additional matrix camera for live previews. It was equipped with a workstation (HP Z2G9, HP, Palo Alto, CA, USA) and the "Batch Scan Wizard" software (version 5.60.122).

Specimens were scanned using international standards: resolution of 600 dpi, labels for each specimen, a 24-color scale (color checker), and a paper ruler as scale bar, crucial for estimation of the sizes of the specimen (Figure 1). The color reference chart (color checker) ensures the proper adjustment of the colors and white balance in the images.

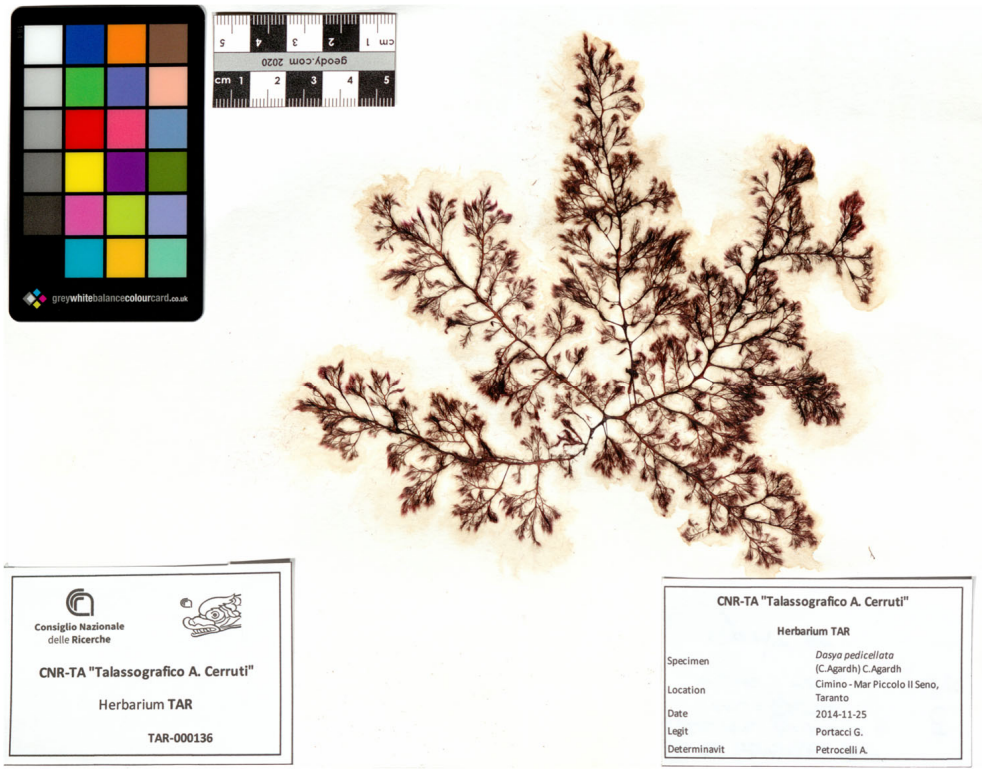


Figure 1. A digitalized image with 2 labels (below), a color checker, and a paper ruler top-left.

Upon scanning, the image has been stored into the associated workstation in *.TIFF format and uploaded to a shared folder on Microsoft Teams®.

For herbarium sheets with a size exceeding the flat-bed dimension of the scanner (460 × 620 mm), a digital camera NIKON Z7 II (NIKON Europe B.V., Amstelveen, The Netherlands) mounted on a lightened stand was also used. Moreover, a digital hand-held microscope Dino-Lite Edge 5MP (Dino-Lite Europe, Almere, The Netherlands) was employed to capture some details.

After scanning, metadata have been collected in a database with fields defined according to the Darwin Core Terminology (https://dwc.tdwg.org) and filled according with the international standards when required. In particular, the ISO standard 8601 [39] and the ISO 3166 [40] were used for recording the sampling date, the country code, and the state/province code (see https://www.iso.org/).

To produce a backup copy, all *.TIFF format images have been stored in physical hard disks preserved at the CNR-IRSA of Taranto for future applications and uses.

Upon completion of the digitization process, metadata publication on the online database GBIF has been started. This activity is still ongoing.

3. Results

To date, the herbarium TAR consists of 507 physical sheets, 394 of which have been included in the digitization process, while 113 have not been digitized since they still

require a careful revision. Indeed, 33 specimens have been identified only at the genus level (e.g., *Ulva* sp., *Valonia* sp.), 65 specimen have been tentatively identified (e.g., *Hypnea* cf. *flexicaulis, Porphyra leucosticta?*), and 15 sheets do not report any taxonomic indication. Since more than one sheet shared the same MIDS, they were scanned into the same image. Thus, 353 digital specimens were obtained at the end of the activities.

Considering the number of specimens imaged and the amount of time required, we calculated an average image rate of 30/day, considering a work day of 6 h.

The herbarium has been built over 43 years, from 1982 to 2025. In this period, three technicians working in the Phycology Laboratory have ruled in the collection of the seaweeds; two researchers were involved in their taxonomic identification. Figure 2 shows two periods in which more samples were collected. The first is the three-year period from 1987 to 1989, in which 84 samples were collected. The second period, from 2009 to 2019, accounted for a total of 182 samples.

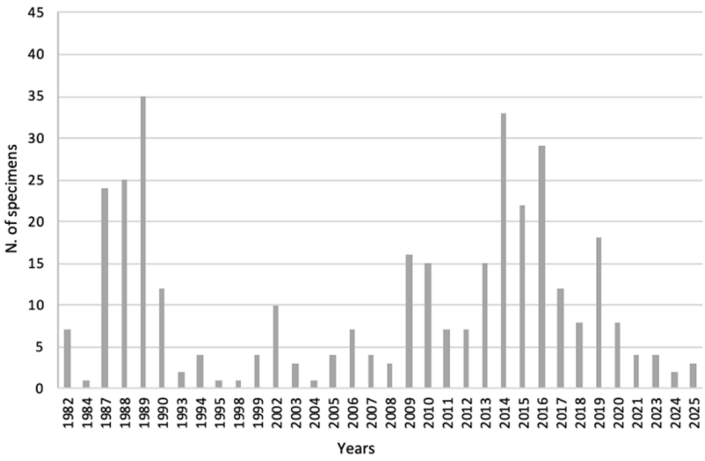


Figure 2. Temporal collection period of specimens preserved at the Herbarium TAR.

The total number of species was 150, comprising 71 Rhodophyta, 29 Chlorophyta, 47 Heterokontophyta, and 3 species of Tracheophyta (Tables 1 and S1).

Table 1. Summary of the results of the Herbarium TAR digitization. The first column reports the phylum, the second column reports the number of species for each phylum, and the third column reports the number of digital specimens for each phylum.

Phylum	Number of Species	Number of Digital Specimens
Rhodophyta	71	217
Chlorophyta	29	54
Heterokontophyta	47	78
Tracheophyta	3	4
Total	150	353

Rhodophyta specimens are represented by 25 families. The dominant family is Rhodomelaceae, which accounts for 18 species (Table 2). An example is reported in Figure 3. Eight families of Chlorophyta are present. The most numerous are Ulvaceae, Codiaceae, and Cladophoraceae, each with 7 species (Table 2). An example is reported in Figure 4a. Heterokontophyta include 13 families, and among them, the most representative is the Sargassaceae family, with 12 species (Table 2). An example is reported in Figure 4b.

Table 2. List of families with the number of species for each phylum.

Rhodophyta		**Chlorophyta**		**Heterokontophyta**		**Tracheophyta**	
Ahnfeltiaceae	1	Bryopsidaceae	1	Agaraceae	2	Cymodoceae	1
Bangiaceae	4	Caulerpaceae	2	Alariaceae	4	Posidoniaceae	1
Bonnemaisoniaceae	2	Cladophoraceae	7	Chordariaceae	4	Ruppiaceae	1
Callithamniaceae	4	Codiaceae	7	Cutleriaceae	1		
Caulacanthaceae	1	Dasycladaceae	1	Desmarestiaceae	2		
Ceramiaceae	2	Halimedaceae	3	Dictyotaceae	6		
Champiaceae	1	Polyphysaceae	1	Fucaceae	5		
Cystocloniaceae	2	Ulvaceae	7	Himanthaliaceae	1		
Delesseriaceae	7			Laminariaceae	4		
Gigartinaceae	2			Lessoniaceae	1		
Gracilariaceae	5			Sargassaceae	12		
Grateloupiaceae	3			Scytosiphonaceae	4		
Halymeniaceae	2			Stypocaulaceae	1		
Kallymeniaceae	1						
Lomentariaceae	1						
Nemaliaceae	1						
Peyssonneliaceae	3						
Phyllophoraceae	2						
Plocamiaceae	1						
Pterocladiaceae	1						
Rhodomelaceae	18						
Rhodymeniaceae	1						
Solieriaceae	3						
Sphaerococcaceae	1						
Wrangeliaceae	1						

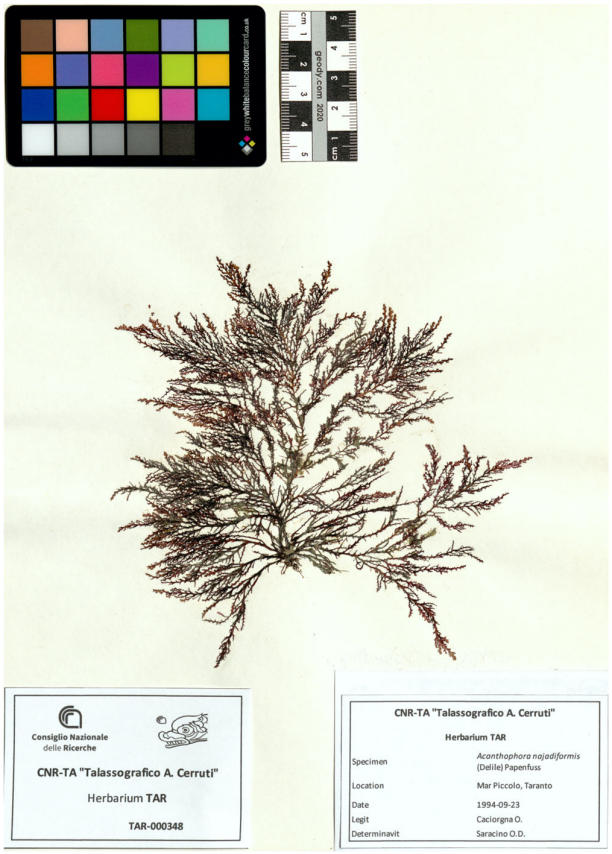


Figure 3. A Rhodophyta specimen from the Herbarium TAR. *Acanthophora najadiformis* (Delile) Papenfuss (Ceramiales, Rhodomelaceae).



(**a**) (**b**)

Figure 4. Chlorophyta and Heterokontophyta samples from the Herbarium TAR: (**a**) *Codium bursa* (Linnaeus) C. Agardh (Chlorophyta, Codiaceae); (**b**) *Sargassum hornschuchii* C. Agardh (Heterokontophyta, Sargassaceae).

Most of the species were collected in the Taranto Seas, the Mar Grande, and the Mar Piccolo (Ionian Sea, southern Italy) (276 samples, 78%). Moreover, several specimens were sampled in other Italian coastal areas (35 samples, 9.9%) and foreign countries such as the Svalbard Islands (Norway), western Canada, and New Zealand. The samples collected at the Italian locations represent 88.1%. There are 19 (5.4%) samples from Canada, 10 (2.8%) from the UK, and 5 (1.4%) from Norway. Samples from France and Israel accounted for 2 (0.6%) and 3 (0.8%), respectively. Samples from Croatia, Mauritania, Malta, New Zealand, and Turkey are the remaining 5 (1.4%).

The herbarium also preserves several specimens of 15 non-indigenous species (NIS), collected in the Mar Piccolo and Mar Grande of Taranto (Table 3; Figure 5).



(**a**) (**b**)

Figure 5. Specimens of non-indigenous species from the Herbarium TAR: (**a**) *Undaria pinnatifida* (Laminariales, Alariaceae); (**b**) *Ascophyllum nodosum* (Fucales, Fucaceae).

Table 3. Seaweed non-indigenous species preserved in the Herbarium TAR.

Species	Year of Collection	Phylum
Agardhiella subulata (C. Agardh) Kraft & M.J. Wynne	1988, 1989, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2023	Rhodophyta
Ascophyllum nodosum (Linnaeus) Le Jolis	2009	Heterokontophyta
Asparagopsis taxiformis (Delile) Trevisan	2018	Rhodophyta
Caulacanthus okamurae Yamada	2017, 2018	Rhodophyta
Caulerpa cylindracea Sonder	1999, 2002, 2007, 2012, 2013, 2014, 2016	Chlorophyta
Codium fragile (Suringar) Hariot	2009, 2013, 2016	Chlorophyta
Colpomenia peregrina Sauvageau	2012, 2016, 2018, 2019	Heterokontophyta
Cutleria multifida (Turner) Greville	2010, 2013	Heterokontophyta
Grateloupia minima P.Crouan & H. Crouan	2010, 2011, 2015, 2016, 2019, 2020, 2023	Rhodophyta
Grateloupia turuturu Y. Yamada	2007, 2008, 2009, 2010, 2013, 2015, 2020	Rhodophyta
Hypnea corona Huisman & Petrocelli	2002, 2003, 2004, 2005, 2014, 2019, 2020	Rhodophyta
Osmundea oederi (Gunnerus) G. Furnari	2007, 2021, 2023	Rhodophyta
Polysiphonia morrowii Harvey	2013, 2014, 2015, 2016, 2018, 2019	Rhodophyta
Solieria filiformis (Kützing) P.W. Gabrielson	1986, 1988, 1989, 1994	Rhodophyta
Undaria pinnatifida (Harvey) Suringar	1998, 1999, 2005	Heterokontophyta

The database of the entire collection was made up of 72 metadata elements for each record and 394 filled records reporting mandatory information (for GBIF standard) (e.g., OccurenceID, BasisOfRecord, ScientificName, InstitutionCode, CollectionCode), strongly recommended information (e.g., EventDate, Country, CatalogueNumber), and recommended if available (e.g., DecimalLatitude, DecimalLongitude). Moreover, other data such as habitat type, morphotype, floating/sessile habitus, sex, presence of reproduction structure, life stage, size, and molecular traits were recorded, if available.

The MIDS level was 2 in most cases, with a few exceptions where insufficient data prevented full compliance with this level. Indeed, information regarding the geographical coordinates of the collection sites was unavailable for 79 specimens, among which there were 35 Rhodophyta, 9 Chlorophyta, and 35 Heterokontophyta, which were collected outside Taranto.

To date, a first data set, as a part of the entire collection, named "The Solieriaceae of the Herbarium TAR" was published on the GBIF portal [41]. It was prepared, including 17 records of species belonging to the mentioned family.

4. Discussion

Today, it is a known fact that herbaria are important for assessing biodiversity changes in a specific geographical area [37,38,42]. Furthermore, having digital botanical data with accurate spatial and temporal positioning is essential for understanding the causes of these changes (e.g., climate change, acidification, eutrophication) also at a broader level [38,43]. According to Davis [5], the ideal perspective is a digital "global metaherbarium" where all the botanical data will be accessible to anyone who needs it for all sorts of reasons, including those not closely related to science, from botanists to ecologists, from chemists to artists.

Most of the exsiccata stored in the Herbarium TAR represent species collected in the Mar Piccolo and the Mar Grande of Taranto over time, where human activities represent the main cause of changes in biodiversity [44]. In particular, the Mar Piccolo is a transitional water system included in the Italian node of the European Research Infrastructure on Long Term Ecosystem Research (eLTER), where a continuous monitoring of the marine macrophyte biodiversity has been carried out for almost forty years, aimed at understanding ecological changes in the ecosystem structure, as well as the dynamics, variability, and

resilience of its communities [44]. The differing number of species recorded over time is due to several reasons. In 1982 and 1984, specimens were collected during single scientific campaigns in the Gulf of Taranto, before the Phycology Laboratory at the Istituto Talassografico in Taranto was established in 1986. The increase in specimens from 1987 to 1990 was a result of the Phycology Laboratory's new activities and the systematic monthly sampling campaigns that followed, which were mainly carried out in Mar Piccolo. The decrease in species richness after 1993 was due to the pollution level of the seawater in 1990–1999 [44] and field activities due to the start of new applicative research activities [45,46]. During the digitization process, the filling of the database made available an immediate tool to search species and make comparisons on the presence/absence of some species in different time periods. For instance, eight samples of Ulvaceae dated between 1987 and 1989 have been detected, while only four samples are dated between 2009 and 2019. This gives a prompt evidence of the considerable reduction in nitrophilous species among the Mar Piccolo seaweeds, starting from 2000 and linked to the improvement of its seawater quality [44].

The Herbarium TAR counts 15 NIS with a different number of exsiccata for each species. This is not surprising since the Mar Piccolo is the third hot spot in the Mediterranean for the introduction of NIS seaweeds [47]. Most likely, the introduction of these species is mainly due to aquaculture activities, as already demonstrated in other transitional water systems [48], while their establishment depends on their tolerance to abiotic factors, especially warm temperatures [47,49]. At present, some of these species are no longer present, such as *Ascophyllum nodosum* and *Undaria pinnatifida*, due to their lack of affinity for the basin temperature [47,50]. The open access availability of digital data on several NIS reported for a particular place, such as the Mar Piccolo, may allow the sharing of information with other researchers who face the same problem in other transitional water systems, making possible inferences about the main vectors responsible for their introduction and the development of good practices and policies to counteract it [51].

5. Conclusions

The collections held in museums, research institutes, and universities around the world, although created for different purposes, can be considered the depositaries of a great quantity of biodiversity data.

The Phycological Laboratory of the Istituto Talassografico of Taranto took the challenge of the project ITINERIS and the DiSSCo Infrastructure to make a macroalgal collection created by researchers who continue to promote long-term ecological studies in a southern region of the Italian peninsula available to the scientific community. The digitization of the Herbarium TAR represents an important initial step toward the enhancement and dissemination of the biodiversity heritage collected over more than forty years of scientific activity. By adopting internationally recognized protocols for image acquisition and metadata curation, and by adhering to FAIR principles, a high-quality digital archive has been created, which will be fully accessible to the global scientific community as soon as possible through platforms such as GBIF. The historical documentation and digital accessibility of these data will provide crucial support for future studies on biogeography, climate change, biological invasions, and marine biodiversity conservation. Further efforts will be focused on implementing the collection in terms of physical samples, digital acquisition, and data sharing. Furthermore, the integration of currently available data with information derived from molecular analyses could be considered to complete the digitization of all the specimens stored in the Herbarium TAR.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d17090641/s1, Table S1: Floristic list in alphabetical order of the seaweed and seagrass species presents in the Herbarium TAR.

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Data Availability Statement: Part of the original data presented in the study are openly available in GBIF at https://doi.org/10.15468/dqnqme (accessed on 11 March 2025). The remainder will be available later from the same repository.

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Abbreviations

The following abbreviations are used in this manuscript:

TAR	Herbarium Istituto Sperimentale Talassografico "A. Cerruti", Taranto
CNR	Consiglio Nazionale delle Ricerche
NRRP	National Recovery and Resilience Plan
ITINERIS	ITalian Integrated Environmental Research Infrastructure System
DiSSCo	Distributed System of Scientific Collections
FAIR	Findable, Accessible, Interoperable, Reusable
GBIF	Global Biodiversity Information Facility
NSCs	Natural Science Collections
MIDS	Minimum Information about a Digital Specimen
GRSciColl	Global Registry of Scientific Collections
NIS	Non-Indigenous Species

References

1. Albani Rocchetti, G.; Armstrong, C.G.; Abeli, T.; Orsenigo, S.; Jasper, C.; Joly, S.; Vamosi, J.C. Reversing extinction trends: New uses of (old) herbarium specimens to accelerate conservation action on threatened species. *New Phytol.* **2021**, *230*, 433–450. [CrossRef]
2. Besnard, G.; Gaudeul, M.; Lavergne, S.; Muller, S.; Rouhan, G.; Sukhorukov, A.P.; Vanderpoorten, A.; Jabbour, F. Herbarium-based science in the twenty-first century. *Bot. Lett.* **2018**, *165*, 323–327. [CrossRef]
3. Heberling, J.M. Herbaria as big data sources of plant traits. *Int. J. Plant Sci.* **2022**, *183*, 87–118. [CrossRef]
4. Heberling, J.M.; Prather, L.A.; Tonsor, S.J. The changing uses of herbarium data in an era of global change: An overview using automated content analysis. *BioScience* **2019**, *69*, 812–822. [CrossRef]
5. Davis, C.C. The herbarium of the future. *Trends Ecol. Evol.* **2023**, *38*, 412–423. [CrossRef]
6. Suarez, A.V.; Tsutsui, N.D. The Value of museum collections for research and society. *BioScience* **2004**, *54*, 66–746. [CrossRef]
7. Mares, M.A. Natural science collections: America's irreplaceable resource. *BioScience* **2009**, *59*, 544–545. [CrossRef]
8. Vellend, M.; Brown, C.D.; Kharouba, H.M.; McCune, J.L.; Myers-Smith, I.H. Historical ecology: Using unconventional data sources to test for effects of global environmental change. *Am. J. Bot.* **2013**, *100*, 1294–1305. [CrossRef]
9. Bradley, R.D.; Bradley, L.C.; Garner, H.J.; Baker, R.J. Assessing the value of natural history collections and addressing issues regarding long-term growth and care. *BioScience* **2014**, *64*, 1150–1158. [CrossRef]
10. Jones, C.A.; Daehler, C.C. Herbarium specimens can reveal impacts of climate change on plant phenology; a review of methods and applications. *PeerJ* **2018**, *6*, e4576. [CrossRef]

11. Grandcolas, P. Natural History Collections: An Ancient Concept in a Present and Future Perspective. In *Natural History Collections in the Science of the 21st Century: A Sustainable Resource for Open Science*; Pellens, R., Ed.; ISTE Ltd: London, UK; Wiley: Hoboken, NJ, USA, 2021; pp. 13–26.
12. Thiers, B.M. Strengthening partnerships to safeguard the future of herbaria. *Diversity* **2024**, *16*, 36. [CrossRef]
13. Ong, T.J.; Leggett, J.J.; Wilson, H.D.; Hatch, S.L.; Reed, M.D. Interactive information visualization in the digital flora of Texas. In *Visual Interfaces to Digital Libraries*; Börner, K., Chen, C., Eds.; Lecture Notes in Computer Science; Springer: Berlin, Germany, 2002; Volume 2539, pp. 188–198. [CrossRef]
14. Harlow, M.; Schmidt, L.; Munoz, P. Digitization of the Grand Teton National Park Herbarium. *UW-Natl. Park Serv. Res. Stn. Annu. Rep.* **2005**, *29*, 27–29. [CrossRef]
15. Flannery, M.C. Plant collections online: Using digital herbaria in biology teaching. *Bioscene J. Coll. Biol. Teach.* **2013**, *39*, 3–9.
16. Seregin, A.P. Making the Russian flora visible: Fast digitisation of the Moscow University Herbarium (MW) in 2015. *Taxon* **2016**, *65*, 205–207. [CrossRef]
17. Seregin, A.P. The largest digital herbarium in Russia is now available online! *Taxon* **2018**, *67*, 463–467. [CrossRef]
18. Popov, D.; Roychoudhury, P.; Hardy, H.; Livermore, L.; Norris, K. The value of digitising natural history collections. *Res. Ideas Outcomes* **2021**, *7*, e78844. [CrossRef]
19. Beaman, R.S.; Cellinese, N. Mass digitization of scientific collections: New opportunities to transform the use of biological specimens and underwrite biodiversity science. *ZooKeys* **2012**, *209*, 7. [CrossRef] [PubMed]
20. Drew, J.A.; Moreau, C.S.; Stiassny, M.L. Digitization of museum collections holds the potential to enhance researcher diversity. *Nat. Ecol. Evol.* **2017**, *1*, 1789–1790. [CrossRef]
21. Nelson, G.; Ellis, S. The history and impact of digitization and digital data mobilization on biodiversity research. *Philos. Trans. R. Soc. B* **2019**, *374*, 20170391. [CrossRef]
22. Niedzielski, P.; Markiewicz, J. Digitalization of herbarium collections as a tool for the commercialization of scientific knowledge. *Procedia Comput. Sci.* **2023**, *225*, 2194–2203. [CrossRef]
23. Hedrick, B.P.; Heberling, J.M.; Meineke, E.K.; Turner, K.G.; Grassa, C.J.; Park, D.S.; Davis, C.C. Digitization and the future of natural history collections. *BioScience* **2020**, *70*, 243–251. [CrossRef]
24. Pandey, R.; Kumar, V. Exploring the impediments to digitization and digital preservation of cultural heritage resources: A selective review. *Preserv. Digit. Technol. Cult.* **2020**, *49*, 26–37. [CrossRef]
25. Corona, L. Digitalization: An overview of the advantages and disadvantages. In *Aspects of Digital Libraries—Digitization, Standards, Open Access, Repositories and User's Skills*; Gabbay, L.K., Ed.; IntechOpen: London, UK, 2023. [CrossRef]
26. Nelson, G.; Paul, D.; Riccardi, G.; Mast, A.R. Five task clusters that enable efficient and effective digitization of biological collections. *ZooKeys* **2012**, *209*, 19–45. [CrossRef] [PubMed]
27. Caspers, M.; Willemse, L.; Raes, N.; Smets, E.; Schalk, P.; Bánki, O.; Gijswijt, G. Quantifying the use of natural history collections. *Biodivers. Data J.* **2024**, *12*, e130811. [CrossRef] [PubMed]
28. Haston, E.; Chapman, C. MIDS: The digitisation standard for Natural Science collections. *Biodivers. Inf. Sci. Stand.* **2022**, *6*, e94604. [CrossRef]
29. Haston, E.; Dillen, M.; Leeflang, S.; Chapman, C. Completing the Completeness Measure: The MIDS Specification. *Biodivers. Inf. Sci. Stand.* **2024**, *8*, e137717. [CrossRef]
30. Wilkinson, M.D.; Dumontier, M.; Aalbersberg, I.J.; Appleton, G.; Axton, M.; Baak, A.; Mons, B. The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* **2016**, *3*, 160018. [CrossRef]
31. Edwards, J.L. Research and societal benefits of the global biodiversity information facility. *BioScience* **2004**, *54*, 485–486. [CrossRef]
32. Cantrill, D.J. The Australasian Virtual Herbarium: Tracking data usage and benefits for biological collections. *Appl. Plant Sci.* **2018**, *6*, e1026. [CrossRef]
33. de la Hidalga, A.N.; Rosin, P.L.; Sun, X.; Bogaerts, A.; De Meeter, N.; De Smedt, S.; Groom, Q. Designing an herbarium digitisation workflow with built-in image quality management. *Biodivers. Data J.* **2020**, *8*, e47051. [CrossRef]
34. Borsch, T.; Stevens, A.D.; Häffner, E.; Güntsch, A.; Berendsohn, W.G.; Appelhans, M.; Zizka, G. A complete digitization of German herbaria is possible, sensible and should be started now. *Res. Ideas Outcomes* **2020**, *6*, e50675. [CrossRef]
35. Powell, C.; Krakowiak, A.; Fuller, R.; Rylander, E.; Gillespie, E.; Krosnick, S.; Shaw, J. Estimating herbarium specimen digitization rates: Accounting for human experience. *Appl. Plant Sci.* **2021**, *9*, e11415. [CrossRef] [PubMed]
36. Hardisty, A.; Saarenmaa, H.; Casino, A.; Dillen, M.; Görddérz, K.; Groom, Q.; Hardy, H.; Koureas, D.; Nieva De La Hidalga, A.; Paul, D.L.; et al. Conceptual design blueprint for the DiSSCo digitization infrastructure-DELIVERABLE D8. 1. *Res. Ideas Outcomes* **2020**, *6*, e54280. [CrossRef]
37. Mannino, A.M.; Armeli Minicante, S.; Rodríguez-Prieto, C. Phycological Herbaria as a useful tool to monitor long-term changes of macroalgae diversity: Some case studies from the Mediterranean Sea. *Diversity* **2020**, *12*, 309. [CrossRef]

38. Bishop, A.M.; Wahlert, G.; Seltman, K. Digitization of the UCSB Herbarium Seaweed Collection Provides Vital Data to Better Understand the Changing Marine Environment; UC Santa Barbara: Cheadle Center for Biodiversity and Ecological Restoration. 2025. Available online: https://escholarship.org/uc/item/27z0f9j7 (accessed on 3 September 2025).
39. *ISO 8601-1: 2019*; Date and Time—Representations for Information Interchange—Part 1: Basic Rules. International Organization for Standardization: Geneva, Switzerland, 2019. Available online: https://www.iso.org/standard/70907 (accessed on 20 January 2025).
40. *ISO 3166-1: 2020*; Codes for the Representation of Names of Countries and Their Subdivisions. Part 1: Country Code. International Organization for Standardization: Geneva, Switzerland, 2020. Available online: https://www.iso.org/standard/72482 (accessed on 20 January 2025).
41. Petrocelli, A.; Papa, L.; Spada, L.; Cecere, E. *The Solieriaceae of the Herbarium TAR*; Consiglio Nazionale delle Ricerche—Istituto di Ricerca sulle Acque: Taranto, Italy, 2025. [CrossRef]
42. Rindi, F.; Bellanti, G.; Annibaldi, A.; Accoroni, S. Reconstructing historical changes in the macroalgal vegetation of a central Mediterranean coastal area based on Herbarium Collections. *Diversity* **2024**, *16*, 741. [CrossRef]
43. Whitley, B.S.; Abermann, J.; Alsos, I.G.; Biersma, E.M.; Gårdman, V.; Høye, T.T.; Jones, L.; Khelidj, N.M.; Li, Z.; Losapio, G.; et al. Harmonising digitised herbarium data to enhance biodiversity knowledge: Major steps towards an updated checklist for the flora of Greenland. *Plants People Planet* **2025**. [CrossRef]
44. Petrocelli, A.; Cecere, E.; Rubino, F. Successions of phytobenthos species in a Mediterranean transitional water system: The importance of long-term observations. *Nat. Conserv.* **2019**, *34*, 217–246. [CrossRef]
45. Petrocelli, A.; Alabiso, G.; Cecere, E.; Aresta, M. The macroalga *Chaetomorpha linum* (*Cladophorales*, *Chlorophyta*): Preliminary Results on its Capability of Atmospheric Carbon Dioxide Mitigation. In Proceedings of the 5th European Meeting on Environmental Chemistry, Bari, Italy, 15–18 December 2004.
46. Cecere, E.; Fanelli, G.; Pierri, C.; Portacci, G.; Cavallo, R.A.; Petrocelli, A.; Stabili, L.; Licciano, M.; Trianni, L.; Giangrande, A. Sustainable Use of Coastal Lagoons: Integrated Polyculture Activity in the Mar Piccolo in Taranto (Southern Italy). In Proceedings of the 2nd International Conference on Coastal lagoons, Klaipeda, Lithuania, 4–9 October 2005.
47. Petrocelli, A.; Wolf, M.A.; Sciuto, K.; Sfriso, A.; Rubino, F.; Ricci, P.; Cecere, E. Long-term data prove useful to keep track of non-indigenous seaweed fate. *Front. Environ. Sci.* **2023**, *11*, 1075458. [CrossRef]
48. Wolf, M.A.; Buosi, A.; Juhmani, A.S.F.; Sfriso, A. Shellfish import and hull fouling as vectors for new red algal introductions in the Venice Lagoon. *Estuar. Coast. Shelf Sci.* **2018**, *215*, 30–38. [CrossRef]
49. Ravaglioli, C.; Benedetti-Cecchi, L.; Bertocci, I.; Maggi, E.; Uyà, M.; Bulleri, F. The role of environmental conditions in regulating long-term dynamics of an invasive seaweed. *Biol. Invasions* **2022**, *24*, 1175–1187. [CrossRef]
50. Cecere, E.; Alabiso, G.; Carlucci, R.; Petrocelli, A.; Verlaque, M. Fate of two invasive or potentially invasive alien seaweeds in a central Mediterranean transitional water system: Failure and success. *Bot. Mar.* **2016**, *59*, 451–462. [CrossRef]
51. Wallace, R.D.; Bargeron, C.T.; Reaser, J.K. Enabling decisions that make a difference: Guidance for improving access to and analysis of invasive species information. *Biol. Invasions* **2020**, *22*, 37–45. [CrossRef]

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