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METHODS ARTICLE

Curation and digitization of insect galls in the collection of the State Museum of Natural History Stuttgart

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Abstract

Although many natural history collections include gall specimens, a uniform curatorial standard remains to be developed. A subset of the gall collection at the State Museum of Natural History Stuttgart served as a model to examine historical methods of gall preservation and explore digitization of specimen data. Six gall storage methods are compared and critically evaluated based on qualitative assessment of specimen condition. Pinning material in insect drawers is recommended, although preservation on herbarium sheets is best suited for digitization and storage in envelopes is the most space-efficient. A gall digitization method is described. Digitized data were used to generate a map, revealing collecting bias and the existence of underexplored areas in terms of gall diversity. Additionally, the systematic treatment of the gall collection yielded new records for the following species in Baden-Württemberg: *Aulacidea hieracii* (Bouché, 1834), *Cynips agama* Hartig, 1840, *Diastrophus rubi* (Bouché, 1834), *Diplolepis nervosa* (Curtis, 1838), *Phanacis centaureae* Förster, 1860, *Xestophanes potentillae* (Retzius in De Geer, 1783) (Hymenoptera: Cynipidae); *Euura pedunculi* (Hartig, 1837) (Hymenoptera: Tenthredinidae); *Rabdophaga albipennis* (Loew, 1850), *Rabdophaga degeerii* (Bremi, 1847), *Rabdophaga heterobia* (Loew, 1850), *Rabdophaga terminalis* (Loew, 1850) (Diptera: Cecidomyiidae); *Aphis symphyti* Schrank, 1801 (Hemiptera: Aphididae); *Livia junci* Schrank, 1789 (Hemiptera: Psyllidae); *Adelges abietis* (L., 1758), *Sacchiphantes viridis* (Ratzeburg, 1843) (Hemiptera: Adelgidae).

Keywords: Baden-Württemberg, digital data, gall midges, gall wasps, Germany, faunistics, natural history collections, oak galls, plant galls.

Zusammenfassung

Obwohl viele naturkundliche Sammlungen Belege von Pflanzengallen enthalten, wurden hierfür keine einheitlichen kuratorischen Standards entwickelt. Ein Teilbestand der Gallensammlung des Staatliches Museums für Naturkunde Stuttgart dient als Modell, um historische Methoden der Aufbewahrung von Pflanzengallen zu untersuchen und die Digitalisierung von Belegdaten voranzutreiben. Sechs Methoden zur Gallenlagerung werden verglichen und basierend auf einer qualitativen Bewertung des Zustands der Sammlungsobjekte bewertet. Das Nadeln von Gallen in Insektenkästen ist unsere empfohlene Aufbewahrungsmethode, obwohl die Fixierung auf Herbarblättern für die Digitalisierung ideal ist und die Aufbewahrung in Umschlägen am platzsparendsten. Ein Verfahren zu Digitalisierung von Gallen wird beschrieben. Mit den Daten wurde eine Verbreitungskarte erstellt, die auf einseitige Sammelaktivitäten und das Vorhandensein wenig untersuchter Regionen hindeutet. Die systematische Aufarbeitung der Gallensammlung brachte für folgende Arten neue Nachweise aus Baden-Württemberg: *Aulacidea hieracii* (Bouché, 1834), *Cynips agama* Hartig, 1840, *Diastrophus rubi* (Bouché, 1834), *Diplolepis nervosa* (Curtis, 1838), *Phanacis centaureae* Förster, 1860, *Xestophanes potentillae* (Retzius in De Geer, 1783) (Hymenoptera: Cynipidae); *Euura pedunculi* (Hartig, 1837) (Hymenoptera: Tenthredinidae); *Rabdophaga albipennis* (Loew, 1850), *Rabdophaga degeerii* (Bremi, 1847), *Rabdophaga heterobia* (Loew, 1850), *Rabdophaga terminalis* (Loew, 1850) (Diptera: Cecidomyiidae); *Aphis symphyti* Schrank, 1801 (Hemiptera: Aphididae); *Livia junci* Schrank, 1789 (Hemiptera: Psyllidae); *Adelges abietis* (L., 1758), *Sacchiphantes viridis* (Ratzeburg, 1843) (Hemiptera: Adelgidae).

Introduction

As the product of an interaction between insect and plant, galls present unique challenges to natural history collections. Traditionally, insects and plants are stored in separate ranges within a museum, and a preserved plant gall may reasonably be placed in a herbarium or in an entomological collection. If the gall inducer is unidentified, disposition becomes more complex, as galls may be induced by fungi, bacteria, nematodes, insects, mites, or parasitic plants. Besides the issue of placement, storage and preservation methods vary wildly, with the result that many gall specimens do not fit neatly into existing museum infrastructure.

Few guidelines exist for curation of gall specimens. However, a well-organized gall collection has great potential to inform research in taxonomy and systematics, as well as ecology, environmental science, and even paleobiology

(Blanes-Dalmau et al. 2017; Knor et al. 2013; Veenstra 2012). Thus, there exists a scientific incentive to standardize gall specimens and make their data available for analysis.

To that end, the present study examines curation and digitization techniques for galls, based on the entomological collection at the State Museum of Natural History Stuttgart (SMNS). The collection includes an estimated 1,000 to 2,000 gall specimens, collected over a period of approximately 200 years. These originate from several continents, including Africa, South America, and Asia, as well as Europe. As one might expect, Germany is especially well-represented.

A large number of unsorted gall specimens at SMNS are stored in three large metal cabinets in the insect collection. Curation methods vary widely and include herbarium sheets, envelopes, albums, file folders, cardboard boxes, and folded newspaper. Prior to the present study, the last examination of the collection occurred in 1995 by Dr. Edwin Möhn (1928–2008), who was a gall midge taxonomist at the SMNS and professor of biology at the University of Stuttgart. However, not all specimens were examined, and a complete catalog of the collection has never been attempted.

Besides the gall cabinets, some galls are pinned in the SMNS dry insect collection next to the insects that emerged from them. Additionally, three drawers of galls can be found in the historical collection of the German entomologist Karl Ludwig Friedrich von Roser (1787–1861). Although he worked as a lawyer and high-level government official in the Kingdom of Württemberg, von Roser had a passion for the natural sciences, especially entomology. He co-founded the "Verein für vaterländische Naturkunde" (Association for Patriotic Natural History) in 1844. His grandchildren donated his collection to the Association in 1872, from where it was transferred to the Stuttgart Museum's ownership (Schüz & Harde 1963). The exact collection dates of his specimens are unknown.

Due to the wide diversity of collecting dates, preservation techniques, host plants, and gall inducers, the SMNS collection provides great opportunity for development of gall curation and digitization techniques. The present study focuses on a subset of the gall collection to promote this neglected aspect of natural history museum studies.

Material and methods

For the present study, all of the galls in the cabinets were examined. All specimens from the federal state of Baden-Württemberg (BW) were selected for further analysis. The total number of gall specimens from BW is 490, collected from 394 unique events. Gall specimens from the cabinets were assembled into a new separate collection. Galls from the von Roser collection and the general pinned insect collection were not removed from their drawers. Storage methods were noted and their relation to the quality and accessibility of the specimens was assessed.

All SMNS collections are databased in the Diversity Workbench (DWB) via the DiversityCollection application (Triebel et al. 1999). New accession numbers (SMNS_Ent_Gall_000001 to SMNS_Ent_Gall_000395) were assigned to the study set. For a better overview, samples were accessioned in order by date of collection, with the oldest specimens assigned the lowest numbers. A distribution map was generated using the mapping function in the DWB.

Taxonomic identifications of gall inducers and host plants were included in the database. All identifications were updated to the most recent nomenclature using GBIF (GBIF.org 2021), Catalogue of Life (Bánki et al. 2022), and Plant Parasites of Europe (Ellis 2021). Original labels were left on the specimens. Two new labels with accession numbers were added: one small round adhesive label and one large paper label (Fig. 1A–C). Unidentified specimens were also accessioned, which would not have been possible using the pre-existing collection ranges.

Sixty-eight specimens were digitally photographed. For imaging, completely identified specimens were prioritized and duplicate representatives of the same gall species were avoided. For each species represented by multiple specimens, the specimen with the best preserved and/or most distinctly developed galls was selected.

Specimens were photographed with a Leaf Credo 80 camera. The Capture One DB 11.3 program was used for image processing and editing. Settings were as follows: aperture F/11; exposure time 1/8 sec; ISO film speed ISO-50; focal length 120 mm; metering mode: center-weighted. Each gall specimen was photographed against a neutral background along with its accession number and specimen label. A color palette, a white balance, and a scale bar were included (Fig. 1A). Images were cropped and the white balance was adjusted. Each file was named for its accession number. The photos were automatically linked to the according datasets in DiversityCollection using the accession numbers. They were also published online via Zenodo (https://doi.org/10.5281/zenodo.6413988).

Results

Storage methods

Six different storage categories were identified from the SMNS gall collection: envelopes, herbarium sheets, albums, folders, boxes, and insect drawers.

Envelopes (Fig. 1B). Envelopes are either prefabricated or fashioned from folded paper by the preservationist. In most cases, the specimen is not externally visible, necessitating removal of the specimen for viewing. A few envelopes are made of transparent material, which becomes porous and brittle over time. Transparent envelopes may also necessitate removal when the specimen is covering the label data.

Herbarium sheets (Fig. 1C). Specimens on herbarium sheets are typically preserved in the classical botanical fashion, attached to a sheet with archival glue or tape. Some older specimens exhibit breakage and partial loss of plant material. Other specimens are attached with non-archival adhesive tape, which in older specimens loses its adhesive ability, resulting in damage. The herbarium sheets are not of uniform size.

Fig. 1. Digitization and storage of gall specimens at SMNS, Stuttgart (Germany). **A**. Digitization layout for gall specimen, including scale bar, white balance, color palette, specimen data, and accession number. **B**. Envelope storage of gall specimens. From left to right: transparent envelope, folded-paper envelope, prefabricated envelope. **C**. Gall specimen stored on a herbarium sheet. **D**. Gall specimens stored in an album.

Album (Fig. 1D). The study set includes one album, created by Antonio Wünsch, a biology teacher with an interest in gall midges, in the early 1970's. This method resembles the herbarium sheet, except that the sheets are bound together at the top. Sheets must be flipped upside down in order to view the specimens on the following pages. Plant material is attached using non-archival adhesive tape, which becomes brown and brittle with time.

Folders (Fig. 2A). Clear plastic folders with galls and labels are filed in a ring binder. Similar to the album, each folder must be flipped to see the specimens on the next page.

Boxes (Fig. 2B). Some galls are stored in small cardboard boxes. Boxes may have an opaque lid, a transparent lid, or no lid at all. The boxes are not of uniform size.

Insect drawers (Fig. 2C). Some galls are pinned in insect drawers, with or without their associated insects. Recently collected specimens are pinned in unit trays, while older ones are pinned directly into a cork-bottomed drawer. The oldest gall specimens from Baden-Württemberg were preserved in this fashion by Karl von Roser in the early to mid 19th century.

Phenology

Galls were collected throughout the year. However, most galls were collected in summer and fall. The top months for collecting were August (142 galls), September (141), and October (69). Seventeen specimens had no collection month data.

Distribution

The distribution map shows all collecting sites in Baden-Württemberg, southwestern Germany (Fig. 3). The most sampled areas were the vicinity of Stuttgart and the western Allgäu near Lake Constance. Out of 395 BW samples in the collection, 120, or about 30%, were collected in the Stuttgart area. In addition, a few were scattered in other parts of the state. Many areas of Baden-Württemberg were not sampled, including ecologically unique areas such as the Black Forest and the Swabian Alps.

Gall hosts

In the collections, nearly all of the galls were found on plant hosts. Two specimens were found on fungi in the family Polyporaceae. Hosts belonged to 27 orders (26 plant orders and one fungus). Host species identification was provided for 312 samples, representing a total of 90 different species. An additional 128 samples had no species identification, but were identified to order, family, or genus. No host was identified for 52 specimens.

The most frequently represented host order was Fagales (206) with 198 specimens identified as *Quercus*. The next most common order was Salicales (148). In the order Rosales, there were 18 specimens, and in the order Coniferales, there are 14 specimens. The remaining 23 orders each included 1–6 specimens.

Gall inducers

There are 370 galls identified to order of gall inducer. Of these, 224 galls were Hymenoptera and 91 were Diptera. Other orders, including mites, bacteria, fungi, and plants, were represented by 55 galls. No order identification was provided for 120 galls. Species identification was provided for 358 specimens, representing 95 gall-inducing species. Many species were represented by multiple specimens. There were 142 galls with no species identification.

Hymenoptera. The study set included 33 species of gall-inducing Hymenoptera: 31 Cynipidae and 2 Tenthredinidae. Twenty-six of the species in the collection are published as occurring in Baden-Württemberg (Huber 1975; Jansen et al. 2018; Pfützenreiter & Weidner 1958). Seven species from the collection have not been previously published for Baden-Württemberg: *Aulacidea hieracii* (Bouché, 1834), *Cynips agama* Hartig, 1840, *Diastrophus rubi* (Bouché, 1834), *Diplolepis nervosa* (Curtis, 1838), *Phanacis centaureae* Förster, 1860, *Xestophanes potentillae* (Retzius in De Geer, 1783) (Cynipidae); and *Euura pedunculi* (Hartig, 1837) (Tenthredinidae).

Diptera. The study set included 26 species of Diptera: 25 Cecidomyiidae and 1 Tephritidae. Skuhravá et al. (2014) listed 139 species for Baden-Württemberg, of which 21 are included in the SMNS collection. Four cecidomyiid species found in the museum collection were previously unrecorded from Baden-Württemberg: *Rabdophaga albipennis* (Loew, 1850), *Rabdophaga degeerii* (Bremi, 1847), *Rabdophaga heterobia* (Loew, 1850), and *Rabdophaga terminalis* (Loew, 1850).

Other insect orders. The study set included 2 species of Coleoptera: *Gymnetron villosulum* Gyllenhal, 1838 and *Thamnurgus kaltenbachi* (Bach, 1849), both of which belong to Curculionidae. No gall-inducing Lepidoptera were identified in the collection. In Hemiptera, 23 species were found from 7 families. Of these, 10 species are not true gall inducers, but are "gall-like" sessile insects preserved on dried plant material. Four species of Hemiptera were not yet listed specifically for Baden-Württemberg: *Aphis symphyti* Schrank, 1801 (Aphididae); *Livia junci* Schrank, 1789 (Psyllidae); *Adelges abietis* (L., 1758), and *Sacchiphantes viridis* (Ratzeburg, 1843) (Adelgidae).

Non-insects. Non-insect gall inducers included 8 species of mites, 4 species of fungus, 1 species of bacteria, and 1 plant species, *Viscum album* (Santalaceae). All of these species have been previously reported from Baden-Württemberg.

Discussion

Gall curation methods

In the following, we discuss the advantages and disadvantages of the six different gall storage types found in this study.

Fig. 2. Digitization and storage of gall specimens at SMNS, Stuttgart (Germany). **A**. Gall specimens stored in clear plastic folders within a 2-ring binder. **B**. Gall specimen stored in a cardboard box with no lid. **C**. Gall specimens stored in an insect drawer, part of the VON ROSER collection.

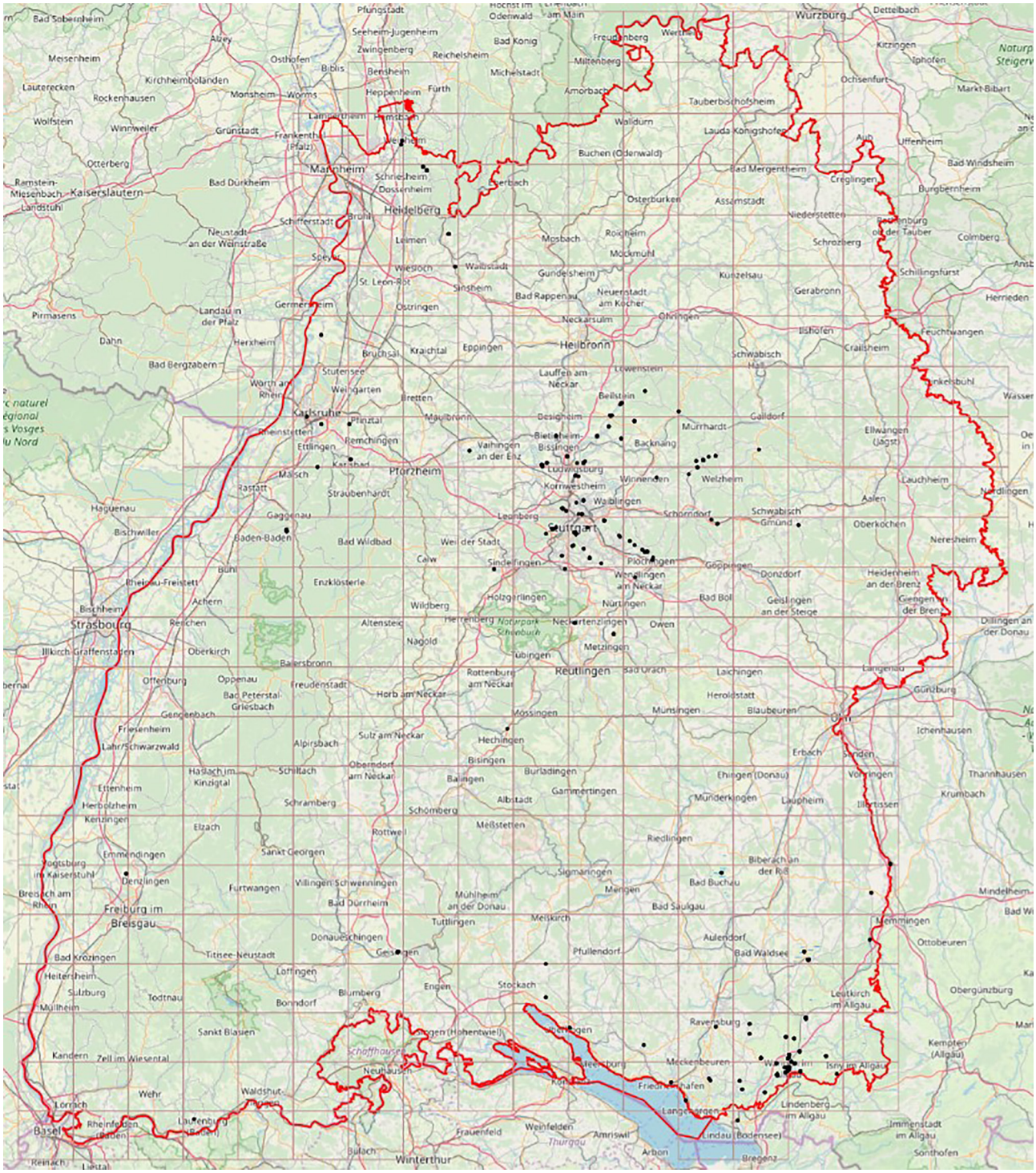

Fig. 3. Map of Baden-Württemberg (SW Germany), showing gall specimen locality data generated via the DiversityWorkbench.

Envelopes are suitable for compact storage of smaller galls, especially for galls on leaves. The envelopes in the collection are quite small, but larger envelopes could be used for larger galls. Folded-paper envelopes are commonly used in the preservation of mosses and lichens. This may explain why the gall collection of Otto Jaap (1864–1922), who was primarily a mycologist and bryologist, is curated in such neatly labeled, uniformly sized envelopes

(Fig. 4A). The JAAP collection is exemplary and the specimens are in excellent condition.

The main disadvantage of the envelope method is that envelopes must be opened to view the specimens. Even in the case of transparent envelopes, the positioning of the specimen often obscures the label data. Opening the envelope and removing the specimen can result in breakage and loss, especially with old and brittle specimens. Additionally, the transparent material is not of archival quality and has deteriorated with age. Despite these limitations, the envelope method is recommended when storage space is limited. Transparent archival plastic envelopes, as are used for Odonata, could provide better visibility and reduce handling.

Herbarium sheets require herbarium cabinets, which are not typically found in an entomology collection. The herbarium sheets in the SMNS insect collection were stacked in large cardboard boxes. The non-uniform size of the herbarium sheets presents another obstacle to their curation. Additionally, only flatter types of galls are suitable for herbarium sheets. Thick, heavy, and protruding galls cause problems with storage and adhesion.

Herbarium sheets provide excellent visibility of the gall, host, and label data. Large amounts of plant material may be preserved, facilitating identification and visual analysis. Thus, herbarium sheets are ideal for digitization. Where herbarium infrastructure is available, this method may be the best option for plant galls, particularly smaller galls that occur on leaves, flowers, or twigs. Archival-quality adhesive is necessary for long-term preservation.

The **album** method of gall preservation appears to be characteristic of ANTONIO WÜNSCH. The collection of *Salix* galls was part of a thesis submitted for his teaching degree. There are several disadvantages resulting from this method. The pages are uneven as a result of the varying thicknesses of the galls and the adhesive tape has deteriorated over time. Also, the album must be flipped through. This means that the specimens are often placed upside down, which can potentially damage them. The risk of parts breaking off and slipping out of the sides is high. In summary, storage as an album should generally be avoided.

Clear plastic **folders** have some advantages over storage as an album. Although the specimens must still be flipped through, the plastic helps to protect them from damage. Thicker galls and hosts are not well-suited to this method. The pages will become uneven and the specimens may be compressed. Thus, uniform storage is not possible. Storage in clear plastic folders is also not generally recommended and it may only be useful for a small reference collection where no collection infrastructure is available.

Cardboard **boxes** can accommodate larger specimens than any of the preceding methods. If the box has a lid, the specimens are well-protected from damage. However, unless the lid is transparent, visibility is low. Additionally, boxes present problems with storage. Much space is needed to store the boxes, and there is no uniform size, which makes it difficult to develop a uniform storage system. Boxes alone are not an ideal gall curation system, although they may be used to store outsized specimens in conjunction with another system.

Pinning galls in **insect drawers** has many advantages. Visibility is excellent, the specimens are well-protected, and the method integrates well with existing insect collection infrastructure. Associated fauna can be pinned next to the gall. The use of unit trays allows for broken pieces of specimens to be retained and reattached. However, a large collection of galls would require a large amount of space, which is often at a premium in entomological collections. Where sufficient drawer space is available, the pinning method is highly recommended. Pinned specimens should have individual labels to ensure that collecting data remains associated. The historical practice of pinning galls next to their labels (Fig. 7) can cause problems when specimens are moved.

In summary, pinning in unit trays is superior when drawer space allows. Herbarium sheets are optimal for digitization and host plant identification, but require appropriate infrastructure. Envelope storage is the most space-efficient method. All three of these methods are suitable for long-term preservation and storage of galls. Albums and folders are not recommended, while boxes should be used only for outsized specimens.

Gall phenology

Although galls were collected throughout the year, most galls were collected in August, September, and October. In Germany, oak galls become particularly conspicuous during this period (BELLMANN et al. 2018). Additionally, the mild weather may encourage outdoor activity, including collecting. Few galls were collected in winter, which is attributable not only to the unpleasant weather but also to the seasonal abscission of leaves.

Besides the VON ROSER drawers, no organisms associated with the galls were found in the 395 objects from the study set. Thus, it is difficult to draw conclusions about their phenology from the preserved material. It is often possible to determine the gall inducer from the appearance of the gall, but it is preferable to store galls along with their inhabitants, including parasites and inquilines.

Collecting bias

A large proportion of known gall-inducing species are insects (STONE & SCHÖNROGGE 2003). Of the gall specimens examined for this project, about 72% were identified as insects. This is not surprising. Besides the fact that insects are diverse and successful gall inducers, we also

Fig. 4. Digitization and storage of gall specimens at SMNS, Stuttgart (Germany). **A**. Digitized gall specimen with folded-paper envelope from the collection of Otto Jaap. **B–D.** Commonly collected oak leaf galls. – **B**. *Cynips longiventris*. **C**. *Neuroterus quercusbaccarum*. **D**. *Macrodiplosis pustularis*.

only examined galls in the entomology collection. It is possible that the SMNS botanical and fungal collections may also include galls, and that the taxonomic diversity of these collections is differently biased.

Oak galls, especially cynipid galls, are conspicuous and oak leaves are readily collected. Thus, oak leaf galls were extremely well-represented in the collection (Fig. 4B–D). The best-represented species were the cynipid wasps *Cynips longiventris* Hartig, 1840 (22 specimens) and *Neuroterus quersusbaccarum* (L., 1758) (40 specimens) and the oak-galling cecidomyiid *Macrodiplosis pustularis* (Bremi, 1847) (29 specimens).

This collecting bias has advantages and disadvantages. A disadvantage, of course, is that many species are not represented in the collection at all. This presents an obstacle to identification and impedes historical research. However, there are advantages to having large amounts of data on a single species. For example, such collections are useful for studying how species respond to climate change, pollution, or habitat destruction over time.

Faunistics

Comprehensive checklists at the state level are not as common in Germany as they are in countries like the USA. However, decisions regarding nature conservation are often made at the state level, so lists of known fauna can help to inform policy makers and scientific advisors. Having a record of what species are present can also aid in the detection of invasive species and in the study of insect decline.

In Baden-Württemberg, partial checklists are available for Cynipidae (Pfützenreiter & Weidner 1958; Huber 1975) and Tenthredinidae (Jansen et al. 2018), while a complete checklist is available for Cecidomyiidae (Skuhravá et al. 2014). Because comprehensive checklists are rare, it is difficult to verify that the 15 species presented here are new records. Rather, they are presented in the interest of completeness and to promote further interest in cataloguing the insect diversity of Baden-Württemberg.

Digitization

Digitization protocols for herbarium specimens are well-developed (Soltis 2017; James et al. 2018). Thus, galls on herbarium sheets are easily incorporated into existing digitization infrastructure. Similarly, specimens in envelopes may be removed and photographed using a botanical system. Specimens bound together in albums or binders are less ideal, due to the awkward positioning necessary to view the pages. Specimens in insect drawers may be digitized using drawer-scanning technology (Schmidt et al. 2012). Odd-sized galls, such as those on fungi (Fig. 6), present the greatest challenge to efficient and consistent digitization.

Digitized data enabled the creation of a map of collecting sites, revealing sampling gaps in some of the most ecologically interesting parts of the state, such as the Black Forest. Further digitization efforts may yield similarly surprising results from beyond the study area. The digitized gall data are now part of the Coding da Vinci project (https://codingdavinci.de) where they are available for use in games, art, and other creative projects.

Future directions

Many problems remain to be solved in both the general area of gall digitization, as well as specifically within the SMNS collection. The present study was not able to determine the methods by which gall specimens were pinned or dried for preservation, nor to provide an analysis of the paper quality used for envelopes and herbarium sheets. The ultimate arrangement of the gall collection is also yet to be determined. One possibility is to organize galls by host plant, which would facilitate research at the ecological community level.

Standardizing the geographical data was labor-intensive and required specialized linguistic and cultural knowledge. Further efforts to streamline the digitization of historical specimens are necessary to acquire larger datasets, which in turn are necessary to understand the effects of climate change and habitat loss on gall-associated communities over time.

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