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ORIGINAL ARTICLE

A treasure trove of plant biodiversity from the 20th century: the Werner Rauh Heritage Project at Heidelberg Botanical Garden and Herbarium

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Abstract Prof. Werner Rauh (1913–2000) was the director at Heidelberg Botanical Garden and Herbarium for several decades and until his retirement in 1994, he undertook more than 36 expeditions, mainly to South and Central America as well as to southern Africa and in particular to Madagascar. From these journeys, he brought back innumerable plants to the Botanical Garden Heidelberg, especially succulents, bromeliads and orchids, which are a valuable part of today's living collection and of the Herbarium. During his expeditions, he wrote more than 90 booklets with detailed information not only about the plants collected, but also about the vegetation and geology of the regions he visited. The heart of the presented Werner Rauh Heritage project is a relational database to store the heterogeneous information found in these field books, as well as to link the information to actual taxonomy and to the garden's existing database, the living collection and numerous plant type material. A number of powerful tools are being developed to enable researchers to search the database for cross-linked information including Rauh's original field numbers and the place of collection. The central part of the Werner Rauh Heritage Project database is a look-up table with the geo-referenced itineraries of Werner Rauh's journeys and another table with all taxa entries listed in any field book. Tables with synonyms, basionyms and protologue data are included as well as numerous images and links to other taxonomic databases such as IPNI and TROPICOS.

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Introduction

Botanical collections are often complex assemblages of different types of information, from dried parts and other objects to living plants. As in many European Botanical Gardens, collections were lost during and after the turmoil of the Second World War and consequently, present-day collections are often the result of the last 65 years of intensive botanical field research as it is the case in Heidelberg. Traditionally, this systematic and taxonomic field work provides the opportunity to collect voucher material for subsequent deposition in herbaria, complementing the living collections and providing long-term references. However, the different types of information and collection objects do require an intelligent strategy to create a synergy between past knowledge and existing collections. For example, living collections with objects of known origin cannot persist over very long time spans, simply because plants will eventually become old and die. Vegetative propagation is not always possible, and many plant species loose their viability gradually. Sexual propagation is possible in many cases, but will genetically alter the collection object so that it does not fit the original collection context anymore (its original collection data, e.g. place of origin and associated genotype). Therefore, it is obvious that there is a great need for collection management to provide not only the opportunity to get access to data, but also to cross-refer many types of information and objects, to maintain the integrity of the collections and to fully explore the existing knowledge.

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There is no doubt about the fact that herbaria and collections are important for many aspects of biodiversity research (Bebber et al. 2010). Furthermore, it is also recognized that out-standing collector personalities make and have made massive and disproportionate contributions (Bebber et al. 2012) to this kind of biodiversity information, and Werner Rauh definitively is among these collectors. At the Heidelberg Botanical Gardens (HEID), most of the 10,000 species under cultivation have been collected from the wild and are fully documented to a large extent. Moreover, this past collection (which represents 65 years of sampling) is also connected to and documented by approximately 350,000 vouchers in the herbarium HEID (many collectors in Heidelberg contributed more than 5,000 vouchers per person since approximately 1950: W. Rauh, K. H. Senghas, W. Hagemann, P. Leins, M. A. Koch), with the vast majority of plants collected by Werner Rauh.

Prof. Werner Rauh (* 16 May 1913 in Niemegk; † 7 April 2000 in Heidelberg) was an internationally renowned and distinguished German botanist. After attending grammar school in Bitterfeld, Rauh studied Botany, Zoology, Chemistry and Geology at the universities of Leipzig, Innsbruck and Halle/Saale, respectively. In 1937, he completed his studies with a doctoral thesis (Rauh 1937). In 1939, he habilitated with the manuscript "Über den polsterförmigen Wuchs" (Rauh 1939) and accepted a position as a university assistant with Prof. A. Seybold at the former Institute for Botany at Heidelberg University. During the Second World War, he served as a meteorologist in the German navy. After the war, Rauh returned to Heidelberg and was appointed associate professor in 1956. In 1960, he became director of the newly founded "Heidelberger Institut für Pflanzensystematik und Pflanzengeographie (Geobotanik)" and director of the Heidelberg Botanical Garden. The latter position he held until 1 year after his retirement in 1981. Werner Rauh was enthusiastic about plant systematics, morphology and biogeography, and from 1950 to 1994, he undertook numerous expeditions, mainly to Africa and South America; his most frequent destinations being Madagascar and Peru (Fig. 1). During these field trips, he discovered and/or described approximately 1,200 plant species, subspecies or varieties. Bromeliads (Rauh 1990), succulents and xerophytes (Rauh 1995, 1998) were the main focus of his research. His herbarium collection (80,000 vouchers collected by W. Rauh himself or close collaborators) is an integral part of the Herbarium (HEID) at Heidelberg University, and many specimens are also to be found in numerous herbaria worldwide. Major parts of his collections of living plants are still cultivated in the Heidelberg Botanical garden, and partly also at Bonn Botanical garden and other collections. His many research expeditions were financed primarily by the "Akademie der Wissenschaften und Literatur zu Mainz" and by the "Heidelberger Akademie der Wissenschaften", both of which he was a member of from 1968 (Mainz) and 1985 (Heidelberg), respectively, until his death in 2000. Rauh's achievements were highly recognized internationally. He was a member of numerous scientific societies and received many honours and distinctions. Ultimately, however, he will probably be best remembered for his description of many new plant taxa from several plant families and for the numerous taxa named in his honour, e.g. *Rauhia* Traub. (Amaryllidaceae) and *Rauhocereus* Backeb. (Cactaceae) from Peru, *Rauhiella* Pabst & Braga (Orchidaceae) from Brazil and the species *Tillandsia rauhii* L.B.Sm. (Bromeliaceae). Further biographical information is published by Drüll (2009) and Hagemann (1978, 1988).

The information and collection resources at Heidelberg Botanical Garden and Herbarium referring to Werner Rauh's botanical activities are comprised not only by living plants and herbarium vouchers, but also include documents from and about his expeditions, e.g. his field books and field diaries. This hand-written archive with more than 17,800 pages in total not only provides information on the various collected plants including collection numbers, but also highlights the socio-cultural context of his work.

Herein, we introduce a project to provide online accessibility of cross-referenced information on the collections and information held at Heidelberg Botanic Garden and in the Herbarium. The knowledge database system was established in 2009 (http://scriptorium.cos.uni-heidelberg.de) and has continuously developed since that time into the current version of "The Werner Rauh Heritage Project".

The Werner Rauh legacy

Field books and field diaries

When Werner Rauh died, he left behind 78 field books with a total of 8,812 hand-written pages, now archived in Bonn, starting with notes on his first 9 months expedition to Peru. These notes resulted later in 267 descriptions of new Cacti-taxa, 243 of them published in Backeberg (1957) and a further 24 newly described species in his monograph "Beitrag zur Kenntnis der peruanischen Kakteenvegetation" (Rauh 1958). The last field book from Madagascar 1994 contains Rauh's last type-collection, *Ceropegia pseudodimorpha*. These field books contain all of Rauh's collection numbers and some additional information allowing the reconstruction of travel itineraries. All of these pages were digitized and are fully accessible online now; furthermore, all data points (accession numbers and species names) were linked with taxonomic data and

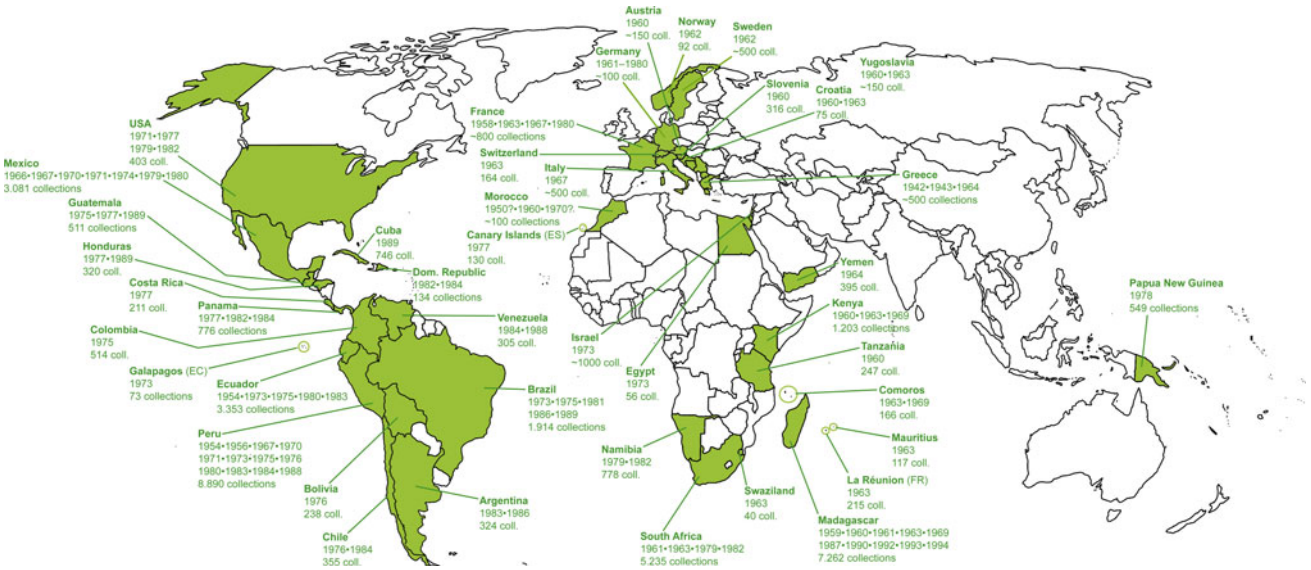

Fig. 1 A summary of Werner Rauh's expeditions from 1942 to 1994 with corresponding collections at HEID. The visited countries are highlighted in *green*, and further detailed information is given on year and respective collection side

species checklists in the WRHP database. Because Rauh did not use consistent numbering schemes throughout his field books, we had to design a unique identifier for each field book and page to link page scans from the database to any sort of related data (Table 1).

The backbone of all information within WRHP are the 80 field books, usually providing lists of collected plants and collections of numbers with more or less exact data on locations and sample areas. These field books represent an extremely valuable source of biodiversity data and are complemented by 94 additional field diaries, archived in Heidelberg. These diaries convey a more detailed view of Rauh's expeditions (itinerary) and often contain very detailed descriptions of collected plants, later used as protologue descriptions in publications. For example, the important P numbers (P, plants collected in Peru 1954 and 1956 excluding Cacti and comprising various type-specimen collections) are documented in Rauh's field diaries only. These diaries, composed of approximately 8,000 pages will be scanned and also incorporated into the database system in the near future. In 2011, 19 lost and previously forgotten field books were found by accident. These books were scanned in autumn 2012, but have not been included into the database up to now.

All 193 books, totalling approximately 17,800 pages, provide important information to be linked to Rauh's herbarium specimen and living plant collection. A list of all field books and field diaries can be viewed in the online database at http://scriptorium.cos.uni-heidelberg.de.

Table 1 Example for the translation of a "unique identifier" of a field book page into its original information

Example code: **HEIDRAUHFDB037_004**	
HEID	Heidelberg Botanic Garden and Herbarium
RAUH	Collection Werner Rauh
FDB	Field book (FDD, field diary, etc.)
037	Booklet No. 37; numbers from 1 to 37 and 40 to 57 were allocated by Karlheinz Senghas, numbers 0A to 0D, 38A to 39 and 58 to 88 were allocated chronologically by us
_004	Scan 4 = original title page of booklet, page 1 (Images 1 to 3 are title page to the project and introduction to each book)

Living collections

From his field expeditions, Werner Rauh brought back thousands of living plants to Heidelberg Botanical Garden. Heidelberg Botanical Garden houses more than 10,000 plant species and ca. 2,100 accessions are actually still linked to original Rauh collection numbers, representing more than 1,200 living plant species. This information is crosslinked with the database. Diagnostic photographs of these plants are also continuously added to the system. Interestingly, 88 living plant accessions are also documented, which served, as it turned out, as original plants for typification and preparation of the holotype by Rauh. The collections at HEID held another 150 living taxa which did serve as material for type specimen preparation, but were collected and described by other botanists. Consequently, additional links were set to type material either preserved as herbarium vouchers or objects preserved in alcohol.

Living collections of material originally collected by Werner Rauh are not maintained in Heidelberg only. Consequently, our project also aims to provide valuable

information for other collections to correctly annotate material obtained from Heidelberg.

Type specimen at Herbarium HEID

From 2009 onwards, 1,236 type specimens from Herbarium HEID (originally collected in Africa) were scanned with high resolution under the auspices of the African Plant Initiative (API), 130 of them collected by Werner Rauh. Besides that a major part of his collection is derived from Latin America, e.g. many species from the Bromeliaceae family. Images of Rauh's African type specimens have recently been included in the WRHP database in lower resolution and are available along with more than 1,200 additional images from the living plant collection of the Botanical Garden Heidelberg. These data are also available via JSTOR as high-resolution images of type specimen and in combination with powerful online exploration and analysis tools provided by that institution, to grant easy access to these biological resources to the countries of origin.

As a first attempt to make available three-dimensional type specimen preserved in alcohol, 400 high-resolution photographs were taken within the recently re-evaluated spirit collection and are incorporated in the database.

Herbarium collections of Werner Rauh

The herbarium collection based on Werner Rauh's scientific work is not fully documented yet. It is composed of more than 80,000 vouchers to date. At the moment, the database system contains the type specimen collections from the herbarium only, and future efforts are necessary to incorporate data of all field collections into the database.

"Rauh-taxa" and type specimen entries in WRHP database

Tropicos lists 609 names with Werner Rauh as author, either as primary or as co-author [www.tropicos.org, accessed 30 July 2012]. IPNI lists in "Index Kewensis" 676 names with Rauh as primary or as co-author, including basionyms [www.ipni.org, accessed 30 July 2012]. Since there are various different states of type specimens to be defined, we defined five main categories: 0 = definitely no type-collection; 1 = definitely a type-collection, which means that entry's type state was confirmed; 5 = possibly a type-collection, e.g. an entry which Rauh indicated as "spec. nov." or "var. nov." in the field book; 9 = no statement possible, e.g. entries without any genus' or species' name. Currently, the database contains 612 entries with type-state 1 ($\approx$90.5 % of "Rauh taxa" in IPNI, and more entries than "Rauh taxa" in Tropicos!) and 293 entries with type state 5 which may be identified as type-collections in the future. During this process of cross-referencing all of the information, 40 herbarium specimens at Herbarium HEID have actually been identified and newly labelled as (Holo-) type specimen.

Photographs

In 2011, we installed a professionally equipped photo studio in the Heidelberg Botanic Garden to take high quality images of plants in the living collection gathered by Werner Rauh. Currently, there are 1,169 images of plants stored in the database, all taken from cultivated plants, which will be uploaded to GBIF and linked to our data soon.

The knowledge database

General concept and ratio

Because Werner Rauh did not develop a unique numbering system for his samples, we had to convert any data point from his collections into a "unique identifier" suitable for entry into a database. Until now, nine such different schemes used by Werner Rauh have been identified (Table 2).

Beyond that, numerous gathering numbers occur with an additional letter (e.g. Rauh 40579a = Type collection of *Fosterella caulescens*) or with added roman number at the end (e.g. Rauh 66210/XVII = *Anthurium* sp.). Rauh used both to distinguish different individuals within one collection or as a correction whenever multiple use of one number for different gatherings occurred.

Consequently, we developed the concept of a "Unique Rauh Collection Identifier" (URCI) translating any collection object or piece of information into a twelve-digit-integer value representing year of gathering, number of field book or field diary volume and field number (Fig. 2).

The backbone of the WRHP database consists of two tables: *tb_entry* containing every occurrence of any field number on any field book page, and *tb_itinerary* containing any waypoints of Rauh's expeditions, disregarding if he collected anything at the corresponding point or not (Fig. 3).

In order to link entries and waypoints with reliable taxonomy and nomenclature, the two tables *tb_taxon* (with taxa based on their basionym) and *tb_synonym* (with all names including basionyms of taxa found in the field books or any other source originating from Rauh), were generated and further linked to the tables *tb_entry* and *tb_itinerary*.

The table *tb_entry* can be divided into four major sections: first section containing data concerning the

Table 2 Nine different numbering schemes used by Werner Rauh

Scheme	Explanation	Example
K with arabic number	Cacti collected in Peru 1954	K 71 = Type collection of *Tephrocactus lagopus* var. *leucolagopus*
K with roman number KI… KXLII and arabic number starting at K43	Cacti collected in Peru 1956	Rauh KXXXIII = Type collection of *Haageocereus smaragdiflorus*
P with arabic number	Plants (except for Cacti) Peru 1954/1956	P493 = Type collection of *Malvastrum peruvianum*
E with arabic number	Plants from Ecuador 1954/56	E130 = *Puya clavata*
M with arabic number	Plants from Madagascar 1959/1960	M1194 = Type collection of *Euphorbia capsaintemariensis*
T with arabic number	Plants from Tanzania 1960	T223 = *Arabis* sp.
Ke with arabic number	Plants from Kenya 1960	Ke867 = Type collection of *Duvalia andreaeana*
KaI with arabic number	Plants from Canary Islands (Spain) 1977	KaI/117 = *Laurus canariensis*
3000 … 74429	Starting 1960 (?) Rauh used single numbers without starting letter(s)	10634 = Type collection of *Cynanchum antandroy*

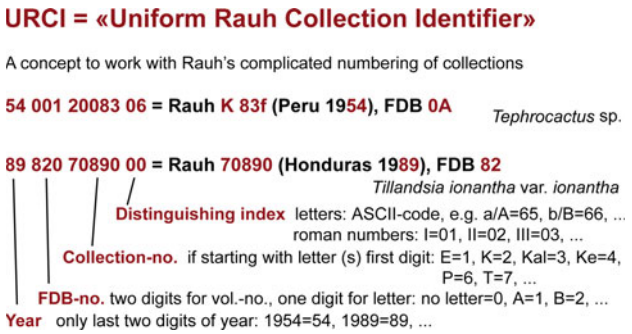

Fig. 2 Examples for two "Unique Rauh Collection Identifiers" (URCI). The first five digits (year and field book number) are subject to change as we noticed starting digitalization of field diaries, that a lot of number intervals are to be found in different field books, e.g. the P- and E- numbers are to be found in 12 field diaries, unfortunately not chronologically or at least in numerical order. This will cause misleading URCIs in future, when these books' data is stored in database, so the first five digits will be replaced by the five-digit-unique-expedition-id introduced in the meantime

gathering/entry itself, such as dataset-id, legname (="Rauh"), legnumber, legdate, sort index (=URCI), link to the entry's source (field book "FDB", protologue "PTL", etc.). The second section is dedicated to nomenclatural and taxonomic data: collected_as_name (the exact spelling of the plant's name, as found in the field book entry), collected part (plant, seeds, herbarium specimen, image, etc.), type collection or not, taxon-id and synonym-id as a connection to the respective tables and any further comments on taxonomy. The third and most extensive section contains location data including collections sites, geo-referenced as accurate as possible, including an estimated precision value. If the gathering was definitely collected at a waypoint already stored in *tb_itinerary*, the id of this waypoint is stored in field itinerary_id. If no waypoint fits the information in the field book, the field is left NULL (i.e. no data available). If any location data is to be found at the entry itself (e.g. name of a place, elevation, etc.), this data is stored in the fields that correspond to the fields in *tb_itinerary*'s second section (cf. next paragraph). The fourth section contains a field for comments and one for the status of the dataset (complete, rudimentary, etc.). The table *tb_ itinerary* is made up of five major sections: the first section contains data referring to the waypoint in a rather technical manner, such as dataset-id, sort index (unified index to allow chronological sorting of waypoints), classification (from "0" for "waypoint is unambiguously given in the field book" to "9" for "waypoint is completely unreliable") and source for waypoint-data (field book, field diary, protologue, herbarium specimen, etc.), also including up to three scan-URLs. The second section contains the real location data, such as country + ISO-code, up to three administrative levels, municipality, location (as spelled in field book) and environment

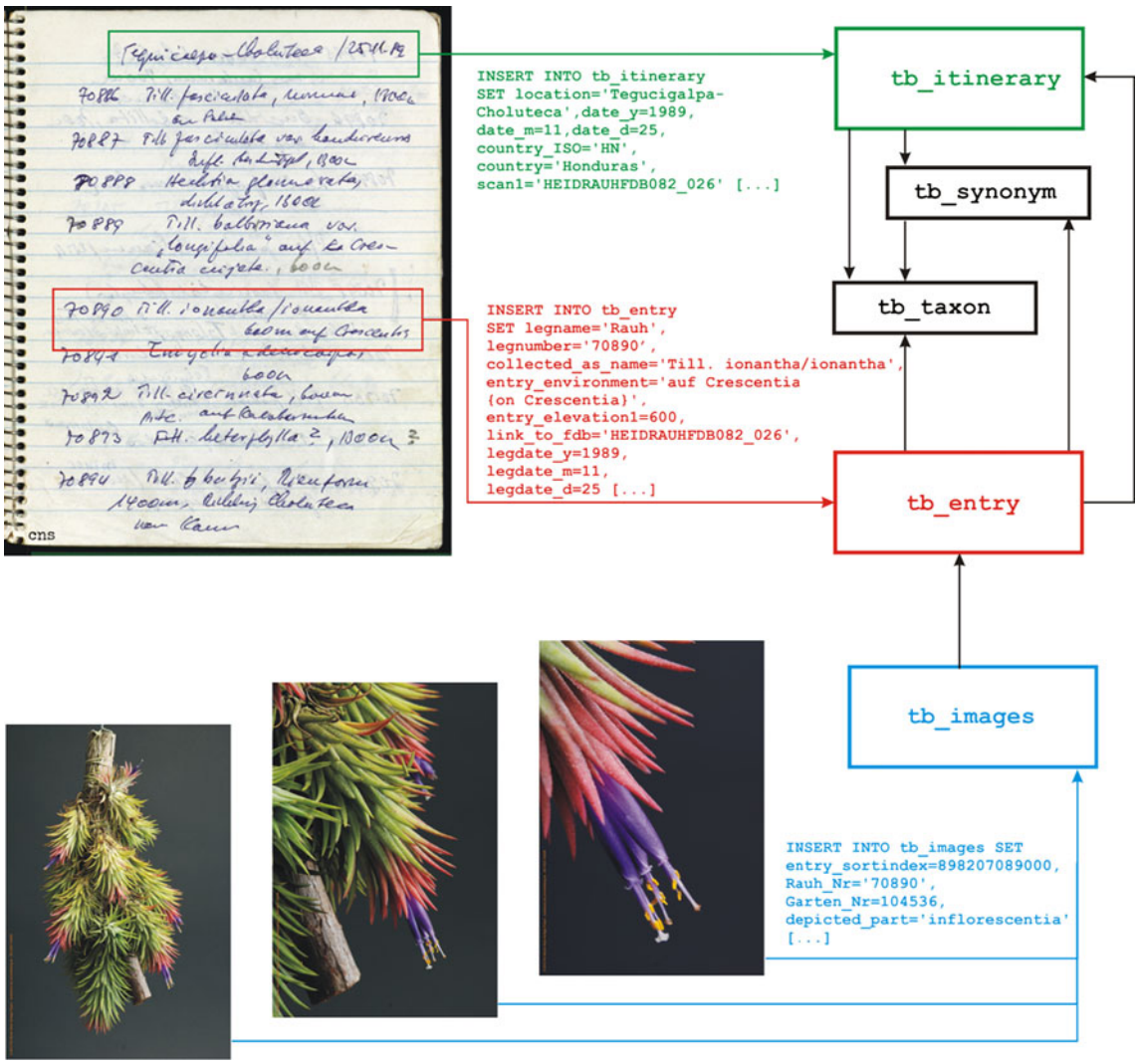

Fig. 3 Schematic structure of the database system (*WRHP* Werner Rauh heritage project). For details refer to the text

(vegetation, soil, etc.). A short third section with one single field can hold additional plant names Rauh observed at the particular location. Often field books do mention plants which were not collected and recorded as a complete entry with field number, etc. For biodiversity research, such information may be no less interesting and helpful than those entries properly identified by field numbers. To link more than one taxon and/or synonym to a waypoint, two separate tables (*tb_itinerary_taxon* and *tb_itinerary_synonym*) are necessary to allow n:m-relations (more than one taxon and synonym, respectively) between waypoints and taxa/synonyms.

A number of further tables allow cross-reference to different data and media such as *tb_images* referencing and linking high-resolution images of plants from Heidelberg Botanic Garden's living collections and of type-specimen in Herbarium HEID to entries within the WRHP database. These references are also used to integrate our images with the corresponding collection data into third party applications, e.g. GBIF or JSTOR. Tables *tb_hrb_herbarium* and *tb_hrb_specimen* are used to store data on herbarium specimen from material collected by Rauh. The first table contains a list of herbaria that keep Rauh-specimen (including information on herbarium acronym, name of institution and interface URL for direct access to herbarium's database, if applicable). The latter contains a list of specimen with gatherings connected to Rauh. Each dataset consists at least of URCI, herbarium acronym and accession number providing a direct link from an entry dataset to the relevant herbarium datasets. Further, data like information on type specimen (Holo, Iso, etc.), quality of material (collected "in the wild" or "ex cult", etc.) or the exact wording of herbarium labels can be added to the table as well as any comments. This feature will be extended in future to build up a "Virtual Herbarium" of Rauh's gatherings, not least of all by providing interfaces for third

parties to submit herbarium data (thus in a way "crowd sourcing" the data acquisition). The planned module could be easily expanded for data from living collections as well ("Virtual Botanical Garden").

The table *tb_FDD* was set up to contain information on Werner Rauh's original field diaries. Information on number of pages, countries affected, date of first entry, date of last entry, etc. can be found in this table. Table *tb_expedition* provides information for all of Werner Rauh's expeditions, which are documented not only in field books and/or field diaries, but also by means of documented herbarium specimens, publications, etc. The table *tb_rauh_maps* contains the metadata of hundreds of original maps from Rauh's expeditions, some of them with very detailed information and annotations on the way he took, locations he collected plant material at and dates and places of overnight stays. These maps are stored with country name, country-ISO-code, year of publication and source or publisher where applicable.

Two approaches to search the database are available: First a java script-based GUI (with access management) to search by plant name, gathering date, location or field number (ID) and second for a simpler, low-threshold search, several PHP-Scripts are in place, accessible via search fields from the start page to quickly search for field numbers or plant names. Finally, we provide parameter sets to directly link to WRHP datasets from third party web pages.

Because of an increasing number of inquiries for "missing Rauh numbers" in the project's database, we added information about those accessions brought or send to the Botanic Garden Heidelberg by a third party (and no direct contribution of W. Rauh). Rauh numbered this material with numbers following the last number used for the last finished expedition, respectively (unfortunately there is a third set of numbers from Rauh's times, called "Garden numbers", but never preceded by Rauh's name and therefore without the risk to be mixed up with "real" Rauh numbers). As the field books represent his own gatherings only, the aforementioned numbers are not accessible the same way as this scanned-in and cross-referenced information. However, this material provided by other botanists has often served as type material, and is therefore frequently cited together with a Rauh number in protologues. In order to make these "Pseudo Rauh numbers" accessible also, a module was added to the database, which contains basic information on the provenance of the material, date of reception and the source of data (usually consisting of acquisition books) for these additional 26,653 numbers. The image module of the database was adjusted to store images of acquisitions with Pseudo-Rauh-numbers as well. The current numbers and status of entries are summarised within Table 3.

Technical realization

Keeping portability in mind, development was done entirely on standard server hardware equipment (FTS Primergy TX300 and Sun StorageTek2510) and easily available, low-cost software. We used a virtual server system, installed as a guest on VMWare ESX and running the latest version of Ubuntu Linux Server edition. The project's software does not rely on this; however, moving to another operating system or DBM is possible with only minor changes. The project is written in server side with PHP5, the database used was MySQL 5; the web server software was a standard installation of Apache 2.2 with PHP and FCGI modules. The client side code generated consists of HTML 4, CSS 4 and Java script. Part of the user interface relies on the JQuery and JQueryUI framework and it is tested with versions 1.7 and 1.4, respectively. Visualisation of geographic data is done with Google Maps; we used the API version 2. With the recent changes in Google's terms of use in mind, we aim at replacing this part of the software with Open Street Map and other Open source GIS products, also allowing the local installation and use of custom maps. For deployment and visualisation of high-resolution images, we employed the IIP Image software (http://iipimage.sourceforge.net) on an Apache-based FCGI server. As a client side viewer for this, we decided to use IIPMooViewer, a java script based image viewer relying on the Mootools library that works well with our IIPImage server. The original TIFF images, as obtained by scanning the field book pages on a Bookeye 3 professional scanner with ImageWare BCS-2 scan and capturing software, were converted batch wise into tiled,

Table 3 Some examples of datasets within WRHP and the number of respective entries (scoring date, 23rd November 2012)

Number	Dataset
33,261	Entries with field number, gathering date, country + ISO, including datasets which are not represented by a field book, e.g. data from protologues
32,671	Entries with field number, gathering date, country + ISO and link to field book scan
31,362	Distinct field numbers
26,653	"Pseudo Rauh-numbers"
4,096	Entries with gathering data, that is at least plant name as written in field book, taxon and/or synonym
2,334	Entries with location data
615	Entries of type-collections
622	Itinerary-points
1,637	Taxa
1,819	Synonyms
1,231	Images of living plants
1,236	Images of type specimens

pyramidal tiffs with low JPEG compression, suitable for FCGI using the open source image manipulation software Imagemagick.

Images of living specimens were taken using a Nikon D90 SLR camera equipped with an AF-S Micro NIKKOR 60 mm 1:2.8 ED lens and professional lighting equipment.

Future perspectives

Currently, the database system focuses on written documents, type material and part of the living collections. One of the collaborative outcomes should exemplify future directions. In collaboration with BGCI (Botanical Garden Conservation International), we uploaded a list of 2,154 taxa (succulent plants only = 14 % of all living accessions at HEID) from the living collection of Botanical Gardens and Herbarium Heidelberg (HEID) to BGCI Plant Search database to support the "BGCI/IOS ex situ cactus and succulent survey 2011". After IOS processed the list and compared it with world-wide collected data, we received a detailed evaluation and a few numbers are highlighted in the following: 294 taxa are categorized as endangered according to IUCN Red List 1997; 188 taxa are categorized as endangered according to IUCN latest Red List; 383 taxa were reported by one location (=BG Heidelberg) only; 112 taxa were reported by two locations, including BG Heidelberg; 109 taxa were reported by three locations, including BG Heidelberg and 50 and 666 records matches taxa protected according to CITES I and CITES II annexes, respectively. These numbers highlight not only the importance, but also the uniqueness of biodiversity explored with WRHP.

The next step is to investigate in more detail the sociocultural background of the various expeditions and to provide this information to researchers and the public also. Furthermore, more exploratory tools should be offered allowing detailed analyses of past biodiversity in the respective countries where Werner Rauh acquired his numerous specimens. As a long-term perspective and in an attempt to make research on "past biodiversity" more meaningful, the large number of vouchers from the herbarium should also be incorporated into the database system.

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