

Standartox: Standardizing Toxicity Data

Andreas Scharmüller ^{1,2,*} , Verena C. Schreiner ¹  and Ralf B. Schäfer ¹ 

¹ iES Landau, Institute for Environmental Sciences, University of Koblenz-Landau, D-76829 Landau, Germany; schreiner-verena@uni-landau.de (V.C.S.); schaefer-ralf@uni-landau.de (R.B.S.)

² Laboratoire d'Hydrologie et de Géochimie de Strasbourg, UMR 7517 CNRS-Université de Strasbourg, 1 rue Blessig, CEDEX, 67084 Strasbourg, France

* Correspondence: andschar@protonmail.com

Received: 10 April 2020; Accepted: 12 May 2020; Published: 16 May 2020



Abstract: An increasing number of chemicals such as pharmaceuticals, pesticides and synthetic hormones are in daily use all over the world. In the environment, chemicals can adversely affect populations and communities and in turn related ecosystem functions. To evaluate the risks from chemicals for ecosystems, data on their toxicity, which are typically produced in standardized ecotoxicological laboratory tests, is required. The results from ecotoxicological tests are compiled in (meta-)databases such as the United States Environmental Protection Agency (EPA) ECOTOXicology Knowledgebase (ECOTOX). However, for many chemicals, multiple ecotoxicity data are available for the same test organism. These can vary strongly, thereby causing uncertainty of related analyses. Given that most current databases lack aggregation steps or are confined to specific chemicals, we developed Standartox, a tool and database that continuously incorporates the ever-growing number of test results in an automated process workflow that ultimately leads to a single aggregated data point for a specific chemical-organism test combination, representing the toxicity of a chemical. Standartox can be accessed through a web application and an R package.

Dataset: <https://doi.org/10.5281/zenodo.3785031>

Dataset License: MIT

Keywords: ecotoxicology; standardization; environmental risk assessment; effect database; database; software; R; API

1. Summary

An increasing number of chemicals such as pharmaceuticals, pesticides and synthetic hormones are in daily use all over the world. In Europe alone, some 100,000 chemicals are estimated to be in current use, whereof 30,000 are produced in quantities larger than one ton per year [1]. Except for pesticides that are released into the environment deliberately, most chemicals enter the environment as a result of their use through different paths (e.g., atmospheric emission and deposition or discharge through wastewater) [2]. In the environment, chemicals can adversely affect populations and communities and in turn related ecosystem functions [3–7]. Ultimately, this may compromise nature's contribution to human well-being, for example the ecosystem services clean drinking and irrigation water as well as food production [8–10]. Pollution with man-made chemicals has been identified as one of three major environmental problems for which research gaps hamper the derivation of planetary boundaries, i.e., thresholds beyond which irreversible state shifts may occur [11,12]. Bernhardt et al. [13] argue that the knowledge gap how chemicals affect populations, communities and in turn ecosystem functions and services, may impede the accomplishment of the Sustainable Development Goals [14] of the United Nations. Even highly regulated chemicals, such as pesticides have been shown to cause strong

adverse effects on non-target organisms, such as birds [5], aquatic insects [15] or fish [10], questioning the current regulation efforts [16].

To evaluate the risks from chemicals to ecosystems, data on their toxicity are required, which is typically produced in standardized ecotoxicological laboratory tests. For example, Morrissey et al. [17] used ecotoxicological test results from 49 insects and crustaceans to evaluate the effect of neonicotinoid insecticides in the aquatic ecosystem. Furthermore, Malaj et al. [4] compiled experimental toxicity test results for 223 chemicals to assess the risk from chemicals to freshwater ecosystems in Europe. Similarly, permissible environmental concentrations are often derived from these test data, typically by a combination with safety factors to account for uncertainties. The test data mainly relate to a few, well tested, standard organisms, such as the brown rat *Rattus norvegicus*, the water flea *Daphnia magna* and the microalga *Raphidocelis subcapitata*. Nevertheless, a much greater variety of organisms has been used in ecotoxicological experiments.

To date, only few initiatives exist that aim to create a public resource of ecotoxicological data, such as the United States Environmental (EPA) Protection Agency ECOTOXicology Knowledgebase (ECOTOX) (ca. 1,000,000 test results, 13,000 taxa, 12,000 chemicals) [18], the German Environmental Agency's Information System Ecotoxicology and Environmental Quality Targets (ETOX) [19], the Pesticides Properties DataBase (PPDB) (ca. 2000 pesticides) [20] or the EnviroTox database [21,22]. The former two compile all available results from experiments into a database. However, for many chemicals, multiple ecotoxicity values are available for the same test organism. These can vary strongly, thereby causing uncertainty of related analyses [23,24]. Moreover, the lack of associated quality information and heterogeneous units hamper reproducible science. The PPDB database, in contrast, provides single ecotoxicity values only for pesticides and a few selected test organisms, thereby covering only a minor fraction of the vast amount of ecotoxicological data. The EnviroTox database is limited to aquatic organisms. Moreover, data analyses often require links to additional data resources, for example to append additional chemical and species information (e.g., chemical properties, habitat of species), which calls for more automated procedures.

We therefore developed Standartox, a tool and database that aims to overcome the limitations of other databases by continuously incorporating the ever-growing number of test results in an automated process workflow that ultimately leads to a harmonized ecotoxicity data collection and provides methods to derive single aggregated ecotoxicity values for a specific chemical-organism test combination. Standartox makes use of the publicly available and quarterly updated ECOTOX database [25] and restricts the data to commonly used endpoints in ecotoxicology, such as half maximal effective concentrations (EC₅₀) or no-observed-adverse-effect concentrations (NOEC), leading to about 600,000 ecotoxicological test results, including about 8000 chemicals, tested on about 10,000 taxa in the current version. Standartox users can filter test results according to several parameters, e.g., refining a search for ecotoxicity data on organisms occurring in specific habitats or regions of the world. Above all, Standartox aggregates ecotoxicological test results in a standardized way, by calculating the minimum, the geometric mean and the maximum of the results for each chemical and the associated, user-defined test parameters. Hence, this reduces the variability between risk assessments that are due to the selection of different ecotoxicological test data [23]. Thereby, Standartox provides the basis for reproducible science and combines information from different sources to simplify the derivation of risk indicators such as Species Sensitivity Distributions (SSD) and Toxic Units (TU), which represent two prominent concepts to assess effects on organisms in ecotoxicology [26–28]. Besides aggregating ecotoxicological test results, Standartox provides a concise overview of the tested chemicals, allowing the identification of potential knowledge gaps. Moreover, Standartox could help in reducing the millions of animals used for toxicity testing each year by facilitating access to ecotoxicity data, which are in favor of, for example, the guidelines by the Organisation for Economic Co-operation and Development (OECD) [29,30]. Standartox comes with two front-ends, a web application (<http://standartox.uni-landau.de>) and the R [31] package *standartox*, providing convenience structures and thereby largely reducing processing time for users.

2. Data Description

Standartox constitutes a collection of quality checked ecotoxicological test results. It is build on the ECOTOX database [25] whose data are processed, cleaned and harmonized to retrieve comparable toxicity endpoints. Subsequently, filter and aggregation methods are created to allow for the retrieval of single toxicity equivalents for specific experimental conditions. The ECOTOX database is updated quarterly, providing on average 5228 (2014–2019) new toxicity entries. These are included in Standartox with each update.

2.1. Filters

The data can be restricted to the three endpoint groups, namely half maximal effective/lethal concentration/dose values (e.g., EC_{50} , LD_{50}), henceforth abbreviated as XX_{50} , lowest observed effect concentrations/levels (LOEC/L), henceforth abbreviated as LOEX and no observed effect concentrations/levels (NOEC/L), henceforth abbreviated as NOEX (Table A2). Standartox allows the ecotoxicity data to be filtered by effect groups (e.g., mortality, population, growth) (Figure 1A) and concentration types (e.g., formulation, active ingredient) as well as test durations (in hours). In addition to these test-specific parameters, Standartox data entries can be filtered by chemical-specific parameters such as the CAS number and chemical roles (e.g., pesticides, metals, drugs) (Figure 1B) and classes (e.g., organochlorine, triazine) (Figure 1C). Furthermore, the Standartox data can be refined to certain taxonomic groups (Figure 1D) as well as organism-specific parameters, such as the organisms' habitat (e.g., freshwater, marine, terrestrial) (Figure 1E) and distribution (e.g., Europe, South America) (Figure 1F).



Figure 1. Share of 10 most frequent entries for the parameters (A) effect group, (B) chemical role, (C) chemical class, (D) taxonomic order, (E) organism habitat and (F) organism distribution in Standartox. Multiple classifications are possible (e.g. a chemical can be a fungicide and a pesticide).

2.2. Aggregation

Typically, species exhibit a differential sensitivity towards chemicals (Figure 2A). Moreover, multiple ecotoxicity values are available for individual species-chemical combinations and these can also exhibit high variability due to several factors such as durations of ecotoxicity tests (Figure 2B), experimental conditions and physiological or genetic fitness differences between test individuals or populations. Not every factor is recorded though, leading to unexplainable variability (Figure 2C). To aggregate multiple ecotoxicity values into a single value on the desired taxonomic level (e.g., for an individual species, across species of a genus or family), and chemical grouping (e.g., across all pesticides), Standartox provides several aggregation methods including the minimum, the maximum and the geometric mean allowing to aggregate the filtered data set. The geometric mean is preferred in comparison to the arithmetic mean, because it is less influenced by outliers and is suitable for skewed data. Furthermore, the geometric mean is preferable over the median, because the median completely ignores the tails of the data distribution, making it unreliable for small data sets [32]. Posthuma et al. [33] showed the usefulness of SSDs and its underlying geometric mean aggregations when assessing environmental effects of chemicals. In the course of the aggregation process, outliers that exceed 1.5 times the interquartile range are flagged to caution Standartox users. However, they are considered in the aggregation, given that the geometric mean is relatively robust against outliers. Overall, Standartox provides a harmonized and reproducible approach to aggregate ecotoxicity data.

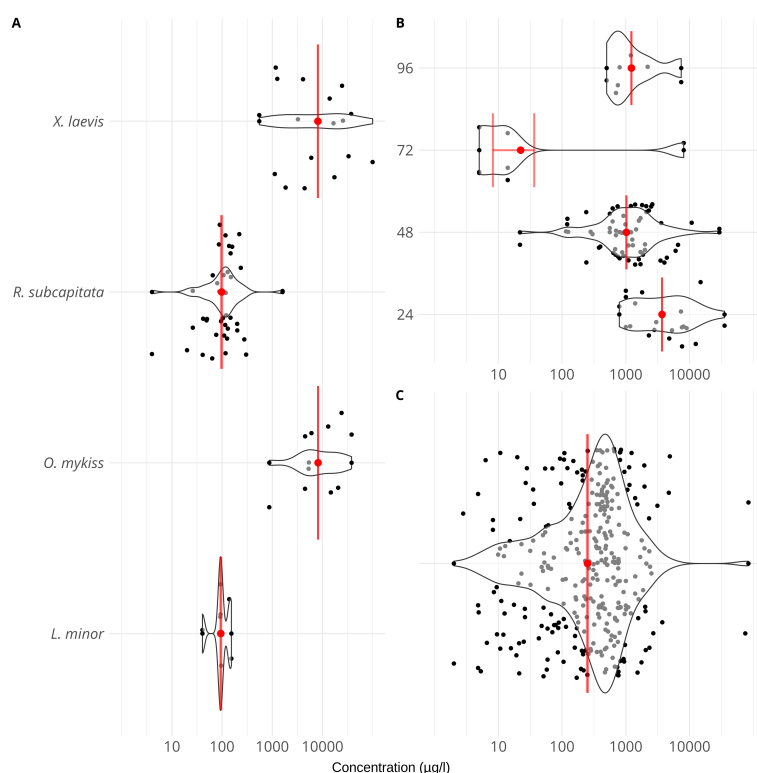


Figure 2. Violin plots of test results (XX_{50}) in Standartox illustrating (A) differential variability and data distribution between species (i.e., *Xenopus laevis*—Amphibian, *Raphidocelis subcapitata*—Algae, *Oncorhynchus mykiss*—Fish, *Lemna minor*—Macrophyte) for the chemical atrazine in 96 h tests, (B) how the variability in toxicity tests with zinc sulfate and *Daphnia magna* varies with test duration and (C) high variability that is not explained by the available test characteristics in the case of cupric sulfate tested on *Pimephales promelas* for 96 h. Red dots depict Standartox geometric mean estimates and red error bars show the associated standard deviation. Black dots depict the raw data. To facilitate readability, data points are randomly scattered along a hypothetical y-axis and are greyed out if within the violins.

2.3. Accuracy Assessment

To validate Standartox results we compared geometric means resulting from the aggregation in Standartox to the corresponding values from other databases, for chemicals where data were available in both resources. The PPDB provides ecotoxicity data on a few selected species commonly used in chemical risk assessment, that have been manually quality controlled through expert judgment [20]. The vast majority of aggregated values (91.9%) of Standartox lie within one order of magnitude of the corresponding PPDB values ($n = 3601$). This would increase to 92.6%, when restricting the comparison to Standartox values where data from at least five experiments are available. Similarly, we compared Standartox to ecotoxicity values for *Daphnia magna* from the ChemProp [34] software, which estimates LC_{50} values via quantitative structure-activity relationship (QSAR) models [35]. We found that 95% of Standartox values lie within one order of magnitude of the ChemProp ($n = 179$) values. However, the difference is not necessarily an indication of lower quality of Standartox estimates but may also reflect the wider range of experimental conditions for which data are available in the database underlying Standartox as well as inaccurate predictions for QSAR models, respectively (Figure 3).

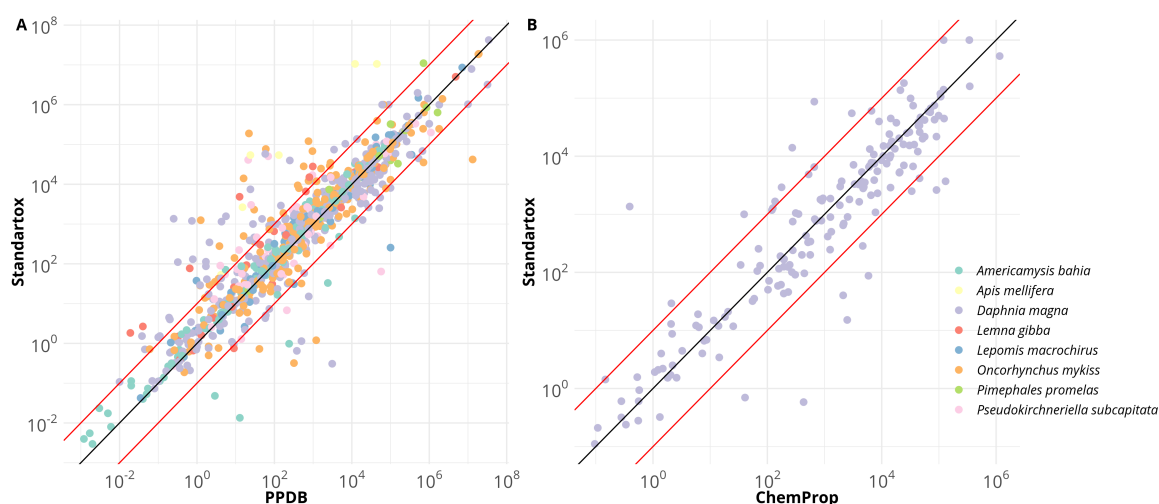


Figure 3. Comparison between Standartox, (A) the Pesticides Properties DataBase (PPDB) and (B) ChemProp values. The black lines indicate identity and red lines mark a divergence of a factor of 10. Compared species are color coded.

2.4. Perspectives

Novel predictive frameworks incorporating chemical mode of action and species traits emphasize the need for holistic and automated analyses of large-scale ecotoxicological data [36,37]. Indeed, the increasing amount of data from ecotoxicological tests and experiments that is becoming available has elicited several initiatives to harmonize these data. These initiatives partly aim for overlapping goals, yet have limitations or objectives that distinguish them from Standartox:

Comptox, is a web tool published by the EPA which, similar to Standartox allows for filtering test results, the retrieval of additional chemical information as well as predicted toxicity data [38], such as 48 h *Daphnia magna* LC_{50} values. However, toxicity estimations are limited to standard test organisms, and the tool lacks the possibility for automated data retrieval [39]. **Comptox** is built on the Aggregated Computational Toxicology Resource (**ACToR**) database, which constitutes the basis for several applications published by the EPA. It collects physicochemical and toxicological data on more than 500,000 environmental chemicals and pharmaceutical compounds from various resources and presents them in a curated list on the web [40,41]. However, no filter mechanisms or aggregation methods are provided in ACToR per se.

The **EnviroTox** database which also uses, amongst others the ECOTOX database as an input has recently been published [21,22]. In contrast to Standartox, EnviroTox is restricted to selected

aquatic organisms (i.e., fish, amphibians, invertebrates and algae) and experimental durations (at least 24 h) and uses a rule-based algorithm to derive single ecotoxicity values. Besides, EnviroTox provides additional information on toxicity endpoints, such as acute or chronic classifications and mode of action assignments. We intentionally omitted such classifications given that the approach to classification may vary with the purpose of the study or because of different classification schemes [42]. The EnviroTox database allows for an aggregation into single toxicity values for individual taxa, whereas Standartox performs this aggregation for individual chemical-taxa combinations. However, the Standartox results for individual taxa-chemical combinations could easily be aggregated across chemicals in a second step to provide a similar aggregation as that performed in EnviroTox.

The **Etox** database collects ecotoxicity test information and provides methods to filter those. Like the ECOTOX database, it also lacks methods to perform aggregations of the ecotoxicity data and only provides manual (non-automated) access. In contrast to the latter, the Etox database can not be downloaded as a whole.

The **PPDB** provides data only on pesticides, and as mentioned before, it provides single quality controlled values only for commonly used taxa, e.g., *Daphnia magna* or *Raphidocelis subcapitata*.

In summary, none of the above mentioned initiatives aim for an automated and standardized aggregation method of exposure endpoints for individual chemicals. In addition, they lack the possibility to access the databases through a common high level programming language, such as R. An overview of the filter and aggregation methods as well as the accessibility of the presented databases is presented in Table 1.

Table 1. Overview on databases that provide ecotoxicological data. Abbreviations: ALL: Most important test parameters, including chemical, taxon, duration for filtering ecotoxicological data are incorporated. Web: Accessible via a web application through a graphical user interface. API: Accessible via an application programming interface.

Database	Filter	Aggregation, Selection	Access
Comptox [39]	Chemical	no	Web, file
Ecotox [25]	ALL	no	Web, file
EnviroTox [21]	ALL	chemical, organism	Web
Etox [19]	ALL	no	Web
Pesticides Properties DataBase (PPDB) [20]	fixed values	manual selection	Web, file
Standartox	ALL	chemical, organism	API, Web

As outlined above, toxicity estimates from different studies can vary strongly due to a wide range of experimental conditions such as pH, temperature and conductivity [43,44]. Integrating these conditions into the aggregated estimates would certainly improve toxicity estimates. However, the current implementation of Standartox omits these conditions, because the ECOTOX database only provides sparse records on experimental conditions. The most frequently provided experimental conditions are temperature (77%), pH (56%), hardness (27%), dissolved oxygen (18%), Alkalinity (15%) and salinity (9%). For all other conditions less than 5% of data entries are available. A text-mining approach, where a literature reference is associated with ecotoxicity raw data, iterating through the individual publications could potentially increase this number, e.g., Compson et al. [45] successfully applied text-mining techniques to retrieve species trait data.

3. Methods

An automated processing pipeline downloads the quarterly released ECOTOX database, performs several preparation steps on it and exports a final Standartox data set. This data set is accessible via a web application and an application programming interface (API). An API provides the means for machine communication between a host and a client and thus allows scriptable data queries. To facilitate the API access, the R [31] package *standartox* is built. All data presented in this paper are derived from the Standartox build, based on the ECOTOX release from the 12.12.2019. The code

for Standartox is located in the two Github repositories *andschar/standartox-build* (<https://github.com/andschar/standartox-build>) and *andschar/standartox* (<https://github.com/andschar/standartox>). The former contains code to process the data and to build the web application and the API, the latter contains code to build the R package. Most of the code is written in R 3.6.1 and associated packages (List: Table A4) and in Structured Query Language (SQL) for PostgreSQL 9.6.1. A graphical overview of the most important processing steps is given in Figure 4.

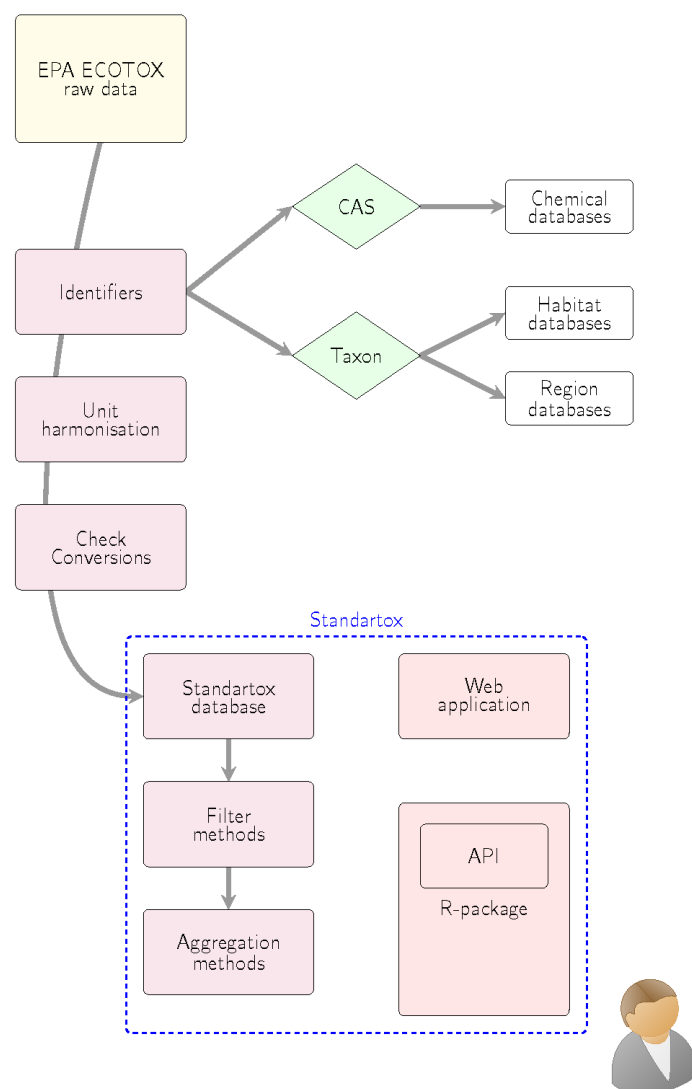


Figure 4. Organigram of Standartox. The U.S. Environmental Protection Agency (EPA) ECOTOXicology Knowledgebase (ECOTOX) is downloaded quarterly and processed (i.e., query additional information with Chemical Abstracts Service (CAS) numbers and taxa names and conversion of concentration and duration units). Subsequently, a Standartox data set is compiled together with filter and aggregation methods. Thus, users can access the Standartox data set and filter and aggregate through a web application and an R package.

3.1. Processing

Standartox downloads the quarterly released ECOTOX database and builds it into a local PostgreSQL database. Subsequently, SQL functions for further processing the data are implemented. In addition lookup tables that enable the conversion of units such as duration and concentration are created. A meta-table providing information, such as the release version of the ECOTOX database is added. Then, provided Chemical Abstracts Service (CAS) numbers and taxonomic names are

used to query additional information from publicly available databases on chemicals and organisms, respectively. This includes the Compendium of Pesticide Common Names [46], the Chemical Entities of Biological Interest (ChEBI) database [47], the Chemical Identifier Resolver (CIR) service [48], the Pubchem database [49], Eurostat [50] and Wikidata [51] for chemicals and the World Register of Marine Species (WoRMS) [52], the Global Biodiversity Information Facility (GBIF) [53] and the freshwater ecology.info database [54] for habitat and spatial distribution of organisms (Table A1). Given that taxonomic names can be ambiguous, e.g., the genus *Eisenia* can refer to an algae and a worm, we first match the taxa names against specific database identifiers and subsequently check their accordance with the underlying ECOTOX data taxonomy. Then, we query the actual data by using the identifiers. In a next step, the data are added to Standartox to enable filtering for specific chemical roles (e.g., drug, metal, pesticide, personal care product) and classes (e.g., pyrethroid, carbamate) as well as spatial distribution (i.e., continents) and habitat preferences (e.g., freshwater) of individual taxa. Taxa that were not identified to at least genus level are excluded, because relative toxicity comparisons have been shown to be not meaningful for higher taxonomic levels [24,55,56]. Finally, the Standartox data set is compiled, which includes the harmonisation of data, e.g., through conversion of test concentration and duration units. 1237 distinct concentration units are converted to six harmonized ones (i.e., g/L, g/m², ppb, g/g, L/L and L/m²) when conversion is possible. Likewise, the 126 distinct duration units are converted to hours whenever this is unambiguously possible. To guarantee appropriate unit conversion and harmonisation, we compared the results of an automated unit conversion to a manual one for each of the distinct concentration and duration units. This assures that 652 of the 1237 concentration units (95.3% of the data) are converted correctly. The remainder could not be converted and is removed. Furthermore, the units are cleaned, for example through removing additional information in the field such as *food*, *soil*, *ai* that are also coded in other variables and hinder the processing of units. Concentrations that are given as rates such as per day (e.g., mg/kg/day) are multiplied by the days of the test and then converted. Experimental endpoints are restricted to three groups, namely NOEX, LOEX and XX₅₀. Other endpoints, such as Bioconcentration factors, non-half maximal effective concentrations (e.g., IC₁₀, EC₂₅, LD₉₉) or maximum acceptable toxicant concentrations are removed. Along with that, a catalog, listing all distinct entries and value ranges, for categorical and continuous variables, respectively, is created. The compiled Standartox data set together with the catalog is exported and accessible via the web application and the API, through the R package.

3.2. Application Methods

When accessed, the web application and the API load the compressed serialized Standartox data into memory and allows the user to interact with them. The user can then call the functions *stx_filter()* and *stx_aggregate()* that filter and aggregate the data according to specific parameters (Table 2). The interactive web application is built in R using the shiny framework, which runs with the help of a shiny server [57]. The API is built by using the R package *plumber* [58], which allows for the creation of Representational State Transfer (REST) APIs from R. REST is a software architectural style that defines web service communication rules. The API is reachable via the Internet Protocol (IP) address 139.14.20.252 and port 8000. Three API-endpoints (*/catalog*, */filter*, and */meta*) can be queried (Table A3). The */catalog* API-endpoint returns a JavaScript Object Notation (JSON) file containing a catalog of possible filter parameters to choose from. The */filter* returns the filtered Standartox table as a compressed serialized binary file created by the R package *fst* [59], to reduce size and allow for fast user queries. Lastly, the */meta* API-endpoint returns a JSON file with meta information, such as the timestamp of the request and the used Standartox version. The API is designed to be used with the R package *standartox* and therefore uses serialization methods specific to R (*rds()* from the R package *base* and *fst()* from the R package *fst*). To facilitate the API usage the R package *standartox* is created.

Table 2. Input parameters for the Standartox web application and the R package *standartox* (CAS—Chemical Abstracts Service Registry number, NOEX and XX₅₀—Standartox endpoints Table A2), vers—Standartox version).

Parameter	Example
cas	7758987, 2921-88-2, 1912-24-9
concentration_type	Active ingredient, Formulation
chemical_role	Antibiotic, Fungicide, Drug
chemical_class	Conazole, Neonicotinoid, Triazine
taxa	Oncorhynchus mykiss, Rattus norvegicus, Daphnia magna
habitat	Marine, Brackish, Freshwater
region	Europe, Africa, Asia
duration	24, 96
effect	Mortality, Population, Growth
endpoint	NOEX, XX50
exposure	aquatic, diet
vers	20191212

4. User Notes

Users can access Standartox either via the web application (<http://standartox.uni-landau.de>) or via the R package *standartox*. By accessing the web application, users can filter and download the resulting data sets as a comma-separated values (csv) file. Users of the R package can directly load the data within R. The R package provides the two functions *stx_catalog()* and *stx_query()*. The first command queries a catalog of possible Standartox parameters into an R list object. The latter allows users to set the Standartox filter parameters and to fetch the actual data. It returns an R list of three tables (i.e., R *data.frames*) containing the filtered data set, the aggregated data set and a table with the meta information retrieved from the API endpoints. A short R-code example is given below (Listing 1) and a detailed description on the usage of the R package is provided on its Github page (<https://github.com/andschar/standartox>).

Listing 1: Sample code to access the Standartox database through the API and the the R package *standartox*. *stx_catalog()* returns a catalog of possible filter and aggregation parameters. *stx_query()* returns the Standartox object, a list of the filtered and the aggregated data as well as a meta data entry. Example for XX₅₀ tests on the chemical glyphosate (CAS number: 1071-83-6) and the taxon *Oncorhynchus* lasting 24 h to 120 h.

```
# install
install.packages('remotes')
remotes::install_github('andschar/standartox')
# retrieve catalog
require(standartox)
catal = stx_catalog()
# retrieve data
l = stx_query(cas = '1071-83-6',
             endpoint = 'XX50',
             taxa = 'Oncorhynchus',
             duration = c(24, 120))
```

5. Conclusions

Due to the steady incorporation of new ecotoxicity data, the aggregated values produced by Standartox can be subject to change with future updates. We regard this as an advantage rather than a drawback because other published works that aim in a similar direction often constitute a singular effort or require manual work for each update. Standartox, in contrast, automates the update process, yet still provides access to its older versions, assuring reproducibility and version control.

In comparison to rule-based approaches for the derivation of single ecotoxicity values, Standartox has the advantage to be free from the subjectivity of a set of human-induced rules. Above all, Standartox provides quick access through its design to be queried via the R language. Due to an increased amount of available ecotoxicological test data, it becomes fundamental to provide and distribute ecotoxicity information in adequate formats, both easily accessible for humans and easily processable for machines. Standartox meets these requirements and puts its focus on the aggregation of toxicity data, thereby adding a piece to the puzzle of modern ecotoxicological data analyses.

Author Contributions: Conceptualization and methods, A.S., R.B.S. and V.C.S.; software development and validation, A.S.; data curation and analysis, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S., V.C.S. and R.B.S.; supervision, R.B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Environment Agency (UBA) grant number 3714 67 4040/2.

Acknowledgments: The authors thank Eduard Szöcs for inspiration through a blog post on how to build a local version of the EPA ECOTOX database.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

API	Application programming interface
CAS	Chemical abstracts service registry number
ChEBI	Chemical Entities of Biological Interest database
CIR	Chemical Identifier Resolver service
E/LC/D ₅₀	Half maximal effective/lethal concentration/dose
XX ₅₀	Summarizes E/LC/D ₅₀ (Table A2)
ECOTOX	US EPA ECOTOXicology Knowledgebase
GBIF	Global Biodiversity Information Facility
JSON	JavaScript Object Notation file format
LOEC/L	Lowest observed effect concentrations/levels
LOEX	Summarizes LOEC/L (Table A2)
NOEC/L	No observed effect concentrations/levels
NOEX	Summarizes NOEC/L (Table A2)
PPDB	Pesticides Properties DataBase
QSAR	Quantitative structure-activity relationship
REST	Representational state transfer software architectural style
SSD	Species sensitivity distribution
TU	Toxic unit
WoRMS	World Register of Marine Species

Appendix A

Table A1. Table of additionally queried publicly available databases and their URLs.

Database	URL
Chemical Entities of Biological Interest (ChEBI)	https://www.ebi.ac.uk/chebi
Chemical Identifier Resolver	https://cactus.nci.nih.gov/chemical/structure
ChemSpider	http://www.chemspider.com
Eurostat	https://ec.europa.eu/eurostat/home
PubChem	https://pubchem.ncbi.nlm.nih.gov
Wikidata	https://www.wikidata.org/wiki/Wikidata:Main_Page
Global Biodiversity Information Facility (GBIF)	https://www.gbif.org
World Register of Marine Species (WoRMS)	http://marinespecies.org
freshwaterecology.info	https://www.freshwaterecology.info

Table A2. Table of how Standartox endpoints are derived from EPA ECOTOX endpoints.

Standartox Endpoint	Ecotox Endpoint	Ecotox Endpoint Description
XX ₅₀	LC ₅₀	Lethal concentration to 50% of test organisms
XX ₅₀	LD ₅₀	Lethal dose to 50% of test organisms
XX ₅₀	EC ₅₀	Effective concentration to 50% of test organisms
XX ₅₀	ED ₅₀	Effective dose to 50% of test organisms
XX ₅₀	IC ₅₀	Inhibition concentration to 50% of test organisms
XX ₅₀	ID ₅₀	Inhibition dose to 50% of test organisms
XX ₅₀	ET ₅₀	Effective response time to 50% of test organisms
XX ₅₀	LT ₅₀	Time to 50% mortality of test organisms
NOEX	NOEC	No-observable-effect-concentration
NOEX	NOEL	No-observable-effect-level
LOEX	LOEC	Lowest observable effect concentration
LOEX	LOEL	Lowest-observable-effect-level

Table A3. Application programming interface (API) endpoints, HTTP methods, Requests and Response objects. JSON—Javascript object notation file.

Endpoint	HTTP Method	Request	Response
/catalog	POST	Standartox version string	Catalog object (JSON)
/filter	POST	Standartox filter parameters	Filtered Standartox data (serialized)
/meta	POST	Standartox version string	Meta data on request (JSON)

Appendix B

Table A4. R packages used for the compilation of the Standartox database.

Package	Description	Citation
bib2df	Parse a BibTeX File to a Data Frame	[60]
countrycode	Convert Country Names and Country Codes	[61]
cowplot	Streamlined Plot Theme and Plot Annotations for 'ggplot2'	[62]
data.table	Extension of 'data.frame'	[63]
DBI	R Database Interface	[64]
dbreport	Automated reports from tables	[65]
devtools	Tools to Make Developing R Packages Easier	[66]
doParallel	Foreach Parallel Adaptor for the 'parallel' Package	[67]
DT	A Wrapper of the JavaScript Library 'DataTables'	[68]
foreach	Provides Foreach Looping Construct for R	[69]
fst	Lightning Fast Serialization of Data Frames for R	[59]
ggplot2	Create Elegant Data Visualisations Using the Grammar of Graphics	[70]
httr	Tools for Working with URLs and HTTP	[71]
jsonlite	A Robust, High Performance JSON Parser and Generator for R	[72]
knitr	A General-Purpose Package for Dynamic Report Generation in R	[73]
openxlsx	Read, Write and Edit xlsx Files	[74]
plotly	Create Interactive Web Graphics via 'plotly.js'	[75]
plumber	An API Generator for R	[58]
R.utils	Various Programming Utilities	[76]
RColorBrewer	ColorBrewer Palettes	[77]
reactlog	Reactivity Visualizer for 'shiny'	[78]
readxl	Read Excel Files	[79]
rgbif	Interface to the Global 'Biodiversity' Information Facility API	[80]
RPostgreSQL	R Interface to the 'PostgreSQL' Database System	[81]
rvest	Easily Harvest (Scrape) Web Pages	[82]
scales	Scale Functions for Visualization	[83]
shiny	Web Application Framework for R	[57]
shinydashboard	Create Dashboards with 'Shiny'	[84]
shinydashboardPlus	Add More 'AdminLTE2' Components to 'shinydashboard'	[85]
shinyjs	Easily Improve the User Experience of Your Shiny Apps in Seconds	[86]
shinyWidgets	Custom Inputs Widgets for Shiny	[87]
stringi	Character String Processing Facilities	[88]
stringr	Simple, Consistent Wrappers for Common String Operations	[89]
taxize	Taxonomic Information from Around the Web	[90]
treemap	Treemap Visualization	[91]
treemapify	Draw Treemaps in 'ggplot2'	[92]
udunits2	Udunits-2 Bindings for R	[93]
webchem	Chemical Information from the Web	[94]

References

- Breithaupt, H. The Costs of REACH. REACH Is Largely Welcomed, but the Requirement to Test Existing Chemicals for Adverse Effects Is Not Good News for All. *EMBO Rep.* **2006**, *7*, 968–971. [[CrossRef](#)] [[PubMed](#)]
- Schwarzenbach, R.P. The Challenge of Micropollutants in Aquatic Systems. *Science* **2006**, *313*, 1072–1077. [[CrossRef](#)] [[PubMed](#)]
- Schäfer, R.B.; von der Ohe, P.C.; Rasmussen, J.; Kefford, B.J.; Beketov, M.A.; Schulz, R.; Liess, M. Thresholds for the Effects of Pesticides on Invertebrate Communities and Leaf Breakdown in Stream Ecosystems. *Environ. Sci. Technol.* **2012**, *46*, 5134–5142. [[CrossRef](#)] [[PubMed](#)]
- Malaj, E.; von der Ohe, P.C.; Grote, M.; Kühne, R.; Mondy, C.P.; Usseglio-Polatera, P.; Brack, W.; Schäfer, R.B. Organic Chemicals Jeopardize the Health of Freshwater Ecosystems on the Continental Scale. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 9549–9554. [[CrossRef](#)]
- Hallmann, C.A.; Foppen, R.P.B.; van Turnhout, C.A.M.; de Kroon, H.; Jongejans, E. Declines in Insectivorous Birds Are Associated with High Neonicotinoid Concentrations. *Nature* **2014**, *511*, 341–343. [[CrossRef](#)]

6. Barra Caracciolo, A.; Topp, E.; Grenni, P. Pharmaceuticals in the Environment: Biodegradation and Effects on Natural Microbial Communities. A Review. *J. Pharm. Biomed. Anal.* **2015**, *106*, 25–36. [CrossRef]
7. Johnston, E.L.; Mayer-Pinto, M.; Crowe, T.P. REVIEW: Chemical Contaminant Effects on Marine Ecosystem Functioning. *J. Appl. Ecol.* **2015**, *52*, 140–149. [CrossRef]
8. Peters, K.; Bundschuh, M.; Schäfer, R. Review on the Effects of Toxicants on Freshwater Ecosystem Functions. *Environ. Pollut.* **2013**, *180*, 324–329. [CrossRef]
9. Van der Sluijs, J.P.; Simon-Delso, N.; Goulson, D.; Maxim, L.; Bonmatin, J.M.; Belzunces, L.P. Neonicotinoids, Bee Disorders and the Sustainability of Pollinator Services. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 293–305. [CrossRef]
10. Yamamuro, M.; Komuro, T.; Kamiya, H.; Kato, T.; Hasegawa, H.; Kameda, Y. Neonicotinoids Disrupt Aquatic Food Webs and Decrease Fishery Yields. *Science* **2019**, *366*, 620–623. [CrossRef]
11. Steffen, W.; Crutzen, P.J.; McNeill, J.R. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. *AMBIO J. Hum. Environ.* **2007**, *36*, 614–621. [614:TAAHNO]2.0.CO;2. [CrossRef]
12. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
13. Bernhardt, E.S.; Rosi, E.J.; Gessner, M.O. Synthetic Chemicals as Agents of Global Change. *Front. Ecol. Environ.* **2017**, *15*, 84–90. [CrossRef]
14. Transforming Our World: The 2030 Agenda for Sustainable Development. In *A New Era in Global Health*; Rosa, W., Ed.; Springer Publishing Company: New York, NY, USA, 2017. [CrossRef]
15. Beketov, M.A.; Kefford, B.J.; Schäfer, R.B.; Liess, M. Pesticides Reduce Regional Biodiversity of Stream Invertebrates. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 11039–11043. [CrossRef] [PubMed]
16. Schäfer, R.B.; Liess, M.; Altenburger, R.; Filser, J.; Hollert, H.; Roß-Nickoll, M.; Schäffer, A.; Scheringer, M. Future Pesticide Risk Assessment: Narrowing the Gap between Intention and Reality. *Environ. Sci. Eur.* **2019**, *31*, 21. [CrossRef]
17. Morrissey, C.A.; Mineau, P.; Devries, J.H.; Sanchez-Bayo, F.; Liess, M.; Cavallaro, M.C.; Liber, K. Neonicotinoid Contamination of Global Surface Waters and Associated Risk to Aquatic Invertebrates: A Review. *Environ. Int.* **2015**, *74*, 291–303. [CrossRef]
18. ECOTOX User Guide: ECOTOXicology Knowledgebase System. Version 5.0. Available online: <https://www.epa.gov/ecotox> (accessed on 1 February 2020).
19. Umweltbundesamt. ETOX: Information System Ecotoxicology and Environmental Quality Targets. 2019. Available online: <https://webetox.uba.de/webETOX> (accessed on 18 December 2019).
20. Lewis, K.A.; Tzilivakis, J.; Warner, D.J.; Green, A. An International Database for Pesticide Risk Assessments and Management. *Hum. Ecol. Risk Assess. Int. J.* **2016**, *22*, 1050–1064. [CrossRef]
21. Health and Environmental Sciences Institute (HESI). *EnviroTox Database & Tools*; Version 1.1.0; HESI: Washington, DC, USA, 2019.
22. Connors, K.A.; Beasley, A.; Barron, M.G.; Belanger, S.E.; Bonnell, M.; Brill, J.L.; de Zwart, D.; Kienzler, A.; Krailler, J.; Otter, R.; et al. Creation of a Curated Aquatic Toxicology Database: EnviroTox. *Environ. Toxicol. Chem.* **2019**, *38*, 1062–1073. [CrossRef]
23. Mark, U.; Solbé, J. Analysis of the Ecetoc Aquatic Toxicity (EAT) Database V— The Relevance of *Daphnia Magna* as a Representative Test Species. *Chemosphere* **1998**, *36*, 155–166. [CrossRef]
24. Malaj, E.; Grote, M.; Schäfer, R.B.; Brack, W.; von der Ohe, P.C. Physiological Sensitivity of Freshwater Macroinvertebrates to Heavy Metals. *Environ. Toxicol. Chem.* **2012**, *31*, 1754–1764. [CrossRef]
25. US EPA. *ECOTOX Knowledgebase*; US EPA: Washington, DC, USA, 2019.
26. Posthuma, L.; Suter, G.W.; Traas, T.P. (Eds.) *Species Sensitivity Distributions in Ecotoxicology*; Environmental and Ecological Risk Assessment; Lewis Publishers: Boca Raton, FL, USA, 2002.
27. Kefford, B.J.; Marchant, R.; Schäfer, R.B.; Metzeling, L.; Dunlop, J.E.; Choy, S.C.; Goonan, P. The Definition of Species Richness Used by Species Sensitivity Distributions Approximates Observed Effects of Salinity on Stream Macroinvertebrates. *Environ. Pollut.* **2011**, *159*, 302–310. [CrossRef] [PubMed]
28. Schäfer, R.B.; Pettigrove, V.; Rose, G.; Allinson, G.; Wightwick, A.; von der Ohe, P.C.; Shimeta, J.; Kühne, R.; Kefford, B.J. Effects of Pesticides Monitored with Three Sampling Methods in 24 Sites on Macroinvertebrates and Microorganisms. *Environ. Sci. Technol.* **2011**, *45*, 1665–1672. [CrossRef] [PubMed]
29. OECD. *OECD Guidelines for the Testing of Chemicals*; OECD: Paris, France, 2020.

30. Hartung, T.; Rovida, C. Chemical Regulators Have Overreached. *Nature* **2009**, *460*, 1080–1081. [[CrossRef](#)] [[PubMed](#)]
31. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
32. Leith, K.F.; Bowerman, W.W.; Wierda, M.R.; Best, D.A.; Grubb, T.G.; Sikarske, J.G. A Comparison of Techniques for Assessing Central Tendency in Left-Censored Data Using PCB and p,p'DDE Contaminant Concentrations from Michigan's Bald Eagle Biosentinel Program. *Chemosphere* **2010**, *80*, 7–12. [[CrossRef](#)]
33. Posthuma, L.; van Gils, J.; Zijp, M.C.; van de Meent, D.; de Zwart, D. Species Sensitivity Distributions for Use in Environmental Protection, Assessment, and Management of Aquatic Ecosystems for 12 386 Chemicals. *Environ. Toxicol. Chem.* **2019**, *38*, 905–917. [[CrossRef](#)]
34. UFZ Department of Ecological Chemistry. *ChemProp* 6.5. 2016. Available online: <http://www.ufz.de/ecochem/chemprop> (accessed on 1 February 2016).
35. Schüürmann, G.; Ebert, R.U.; Kühne, R. Quantitative Read-Across for Predicting the Acute Fish Toxicity of Organic Compounds. *Environ. Sci. Technol.* **2011**, *45*, 4616–4622. [[CrossRef](#)]
36. Malaj, E.; Guénard, G.; Schäfer, R.B.; von der Ohe, P.C. Evolutionary Patterns and Physicochemical Properties Explain Macroinvertebrate Sensitivity to Heavy Metals. *Ecol. Appl.* **2016**, *26*, 1249–1259. [[CrossRef](#)]
37. Van den Berg, S.J.P.; Baveco, H.; Butler, E.; De Laender, F.; Focks, A.; Franco, A.; Rendal, C.; Van den Brink, P.J. Modeling the Sensitivity of Aquatic Macroinvertebrates to Chemicals Using Traits. *Environ. Sci. Technol.* **2019**, *53*, 6025–6034. [[CrossRef](#)]
38. Martin, T.M.; Young, D.M. Prediction of the Acute Toxicity (96-h LC₅₀) of Organic Compounds to the Fathead Minnow (*Pimephales Promelas*) Using A Group Contrib. Method. *Chem. Res. Toxicol.* **2001**, *14*, 1378–1385. [[CrossRef](#)]
39. Williams, A.J.; Grulke, C.M.; Edwards, J.; McEachran, A.D.; Mansouri, K.; Baker, N.C.; Patlewicz, G.; Shah, I.; Wambaugh, J.F.; Judson, R.S.; et al. The CompTox Chemistry Dashboard: A Community Data Resource for Environmental Chemistry. *J. Cheminform.* **2017**, *9*, 61. [[CrossRef](#)]
40. Judson, R.; Richard, A.; Dix, D.; Houck, K.; Elloumi, F.; Martin, M.; Cathey, T.; Transue, T.R.; Spencer, R.; Wolf, M. ACToR—Aggregated Computational Toxicology Resource. *Toxicol. Appl. Pharmacol.* **2008**, *233*, 7–13. [[CrossRef](#)] [[PubMed](#)]
41. Judson, R.S.; Martin, M.T.; Egeghy, P.; Gangwal, S.; Reif, D.M.; Kothiya, P.; Wolf, M.; Cathey, T.; Transue, T.; Smith, D.; et al. Aggregating Data for Computational Toxicology Applications: The U.S. Environmental Protection Agency (EPA) Aggregated Computational Toxicology Resource (ACToR) System. *Int. J. Mol. Sci.* **2012**, *13*, 1805–1831. [[CrossRef](#)] [[PubMed](#)]
42. Kienzler, A.; Barron, M.G.; Belanger, S.E.; Beasley, A.; Embry, M.R. Mode of Action (MOA) Assignment Classifications for Ecotoxicology: An Evaluation of Approaches. *Environ. Sci. Technol.* **2017**, *51*, 10203–10211. [[CrossRef](#)] [[PubMed](#)]
43. Rosenkrantz, R.T.; Cedergreen, N.; Baun, A.; Kusk, K.O. Influence of pH, Light Cycle, and Temperature on Ecotoxicity of Four Sulfonyleurea Herbicides towards Lemna Gibba. *Ecotoxicology* **2013**, *22*, 33–41. [[CrossRef](#)]
44. Li, D.; Zhou, D.; Wang, P.; Li, L. Temperature Affects Cadmium-Induced Phytotoxicity Involved in Subcellular Cadmium Distribution and Oxidative Stress in Wheat Roots. *Ecotoxicol. Environ. Saf.* **2011**, *74*, 2029–2035. [[CrossRef](#)]
45. Compson, Z.G.; Monk, W.A.; Curry, C.J.; Gravel, D.; Bush, A.; Baker, C.J.; Al Manir, M.S.; Riazanov, A.; Hajibabaei, M.; Shokralla, S.; et al. Linking DNA Metabarcoding and Text Mining to Create Network-Based Biomonitoring Tools: A Case Study on Boreal Wetland Macroinvertebrate Communities. *Adv. Ecol. Res.* **2018**, *59*, 33–74. [[CrossRef](#)]
46. Wood, A. *Compendium of Pesticide Common Names*; 2019. Available online: <http://www.alanwood.net/pesticides> (accessed on 1 April 2020).
47. Hastings, J.; Owen, G.; Dekker, A.; Ennis, M.; Kale, N.; Muthukrishnan, V.; Turner, S.; Swainston, N.; Mendes, P.; Steinbeck, C. ChEBI in 2016: Improved Services and an Expanding Collection of Metabolites. *Nucleic Acids Res.* **2016**, *44*, D1214–D1219. [[CrossRef](#)]
48. National Institutes of Health (NIH). *Chemical Identifier Resolver*; NIH: Bethesda, MD, USA, 2019.
49. Kim, S.; Thiessen, P.A.; Bolton, E.E.; Chen, J.; Fu, G.; Gindulyte, A.; Han, L.; He, J.; He, S.; Shoemaker, B.A.; et al. PubChem Substance and Compound Databases. *Nucleic Acids Res.* **2016**, *44*, D1202–D1213. [[CrossRef](#)]
50. European Commission. *Eurostat*; European Commission: Brussels, Belgium, 2019.

51. Vrandečić, D.; Krötzsch, M. Wikidata: A Free Collaborative Knowledgebase. *Commun. ACM* **2014**, *57*, 78–85. [CrossRef]
52. WoRMS Editorial Board. *World Register of Marine Species (WoRMS)*; WoRMS Editorial Board, 2020. Available online: <http://www.marinespecies.org> (accessed on 1 April 2020).
53. GBIF: The Global Biodiversity Information Facility. *What Is GBIF?* 2020. Available online: <https://www.gbif.org/what-is-gbif> (accessed on 1 April 2020).
54. Schmidt-Kloiber, A.; Hering, D. [www.Freshwaterecology.Info](http://www.freshwaterecology.info)—An Online Tool That Unifies, Standardises and Codifies More than 20,000 European Freshwater Organisms and Their Ecological Preferences. *Ecol. Indic.* **2015**, *53*, 271–282. [CrossRef]
55. Rainbow, P.S. Trace Metal Concentrations in Aquatic Invertebrates: Why and so What? *Environ. Pollut.* **2002**, *120*, 497–507. [CrossRef]
56. Buchwalter, D.B.; Luoma, S.N. Differences in Dissolved Cadmium and Zinc Uptake among Stream Insects: Mechanistic Explanations. *Environ. Sci. Technol.* **2005**, *39*, 498–504. [CrossRef] [PubMed]
57. Chang, W.; Cheng, J.; Allaire, J.; Xie, Y.; McPherson, J. *Shiny: Web Application Framework for R*; R package version 1.4.0.2; 2020. Available online: <https://CRAN.R-project.org/package=shiny> (accessed on 1 April 2020).
58. Trestle Technology, LLC. *plumber: An API Generator for R*; R package version 0.4.6; Trestle Technology, LLC: Dallas, TX, USA, 2018. Available online: <https://CRAN.R-project.org/package=plumber> (accessed on 1 April 2020).
59. Klik, M. *fst: Lightning Fast Serialization of Data Frames for R*; R package version 0.9.2; 2020. Available online: <https://CRAN.R-project.org/package=fst> (accessed on 1 April 2020).
60. Ottolinger, P. *bib2df: Parse a BibTeX File to a Data Frame*; R package version 1.1.1; 2019. Available online: <https://CRAN.R-project.org/package=bib2df> (accessed on 1 April 2020).
61. Arel-Bundock, V. *Countrycode: Convert Country Names and Country Codes*; R package version 1.1.1; 2020. Available online: <https://CRAN.R-project.org/package=countrycode> (accessed on 1 April 2020).
62. Wilke, C.O. *cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2'*; R package version 0.9.4; 2019. Available online: <https://CRAN.R-project.org/package=cowplot> (accessed on 1 April 2020).
63. Dowle, M.; Srinivasan, A. *data.table: Extension of 'data.frame'*; R package version 1.12.8; 2019. Available online: <https://CRAN.R-project.org/package=data.table> (accessed on 1 April 2020).
64. R Special Interest Group on Databases (R-SIG-DB); Wickham, H.; Müller, K. *DBI: R Database Interface*; R package version 1.1.0; 2019. Available online: <https://CRAN.R-project.org/package=DBI> (accessed on 1 April 2020).
65. Scharmüller, A. *dbreport: Automated Reports from Tables*; R package version 0.0.0.9007; 2020. Available online: <https://github.com/andschar/dbreport> (accessed on 1 April 2020).
66. Wickham, H.; Hester, J.; Chang, W. *devtools: Tools to Make Developing R Packages Easier*; R package version 2.2.1; 2019. Available online: <https://CRAN.R-project.org/package=devtools> (accessed on 1 April 2020).
67. Corporation, M.; Weston, S. *doParallel: Foreach Parallel Adaptor for the 'Parallel' Package*; R package version 1.0.14; 2018. Available online: <https://CRAN.R-project.org/package=doParallel> (accessed on 1 April 2020).
68. Xie, Y.; Cheng, J.; Tan, X. *DT: A Wrapper of the JavaScript Library 'DataTables'*; R package version 0.7; 2019. Available online: <https://CRAN.R-project.org/package=DT> (accessed on 1 April 2020).
69. Microsoft.; Weston, S. *foreach: Provides Foreach Looping Construct for R*; R package version 1.4.4; 2017. Available online: <https://CRAN.R-project.org/package=foreach> (accessed on 1 April 2020).
70. Wickham, H.; Chang, W.; Henry, L.; Pedersen, T.L.; Takahashi, K.; Wilke, C.; Woo, K.; Yutani, H.; Dunnington, D. *ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics*; R package version 3.3.0; 2020. Available online: <https://CRAN.R-project.org/package=ggplot2> (accessed on 1 April 2020).
71. Wickham, H. *httr: Tools for Working with URLs and HTTP*; R package version 1.4.1; 2019. Available online: <https://CRAN.R-project.org/package=httr> (accessed on 1 April 2020).
72. Ooms, J. *jsonlite: A Robust, High Performance JSON Parser and Generator for R*; R package version 1.6.1; 2020. Available online: <https://CRAN.R-project.org/package=jsonlite> (accessed on 1 April 2020).
73. Xie, Y. *knitr: A General-Purpose Package for Dynamic Report Generation in R*; R package version 1.28; 2020. Available online: <https://CRAN.R-project.org/package=knitr> (accessed on 1 April 2020).
74. Schauburger, P.; Walker, A. *openxlsx: Read, Write and Edit xlsx Files*; R package version 4.1.4; 2019. Available online: <https://CRAN.R-project.org/package=openxlsx> (accessed on 1 April 2020).

75. Sievert, C.; Parmer, C.; Hocking, T.; Chamberlain, S.; Ram, K.; Corvellec, M.; Despouy, P. *plotly: Create Interactive Web Graphics via 'plotly.js'*; R package version 4.9.0; 2019. Available online: <https://CRAN.R-project.org/package=plotly> (accessed on 1 April 2020).
76. Bengtsson, H. *R.utils: Various Programming Utilities*; R package version 2.9.0; 2019. Available online: <https://CRAN.R-project.org/package=R.utils> (accessed on 1 April 2020).
77. Neuwirth, E. *RColorBrewer: ColorBrewer Palettes*; R package version 1.1-2; 2014. Available online: <https://CRAN.R-project.org/package=RColorBrewer> (accessed on 1 April 2020).
78. Schloerke, B. *reactlog: Reactivity Visualizer for 'Shiny'*; R package version 1.0.0; 2019. Available online: <https://CRAN.R-project.org/package=reactlog> (accessed on 1 April 2020).
79. Wickham, H.; Bryan, J. *readxl: Read Excel Files*; R package version 1.3.1; 2019. Available online: <https://CRAN.R-project.org/package=readxl> (accessed on 1 April 2020).
80. Chamberlain, S. *rgbif: Interface to the Global 'Biodiversity' Information Facility API*; R package version 1.3; 2019. Available online: <https://CRAN.R-project.org/package=rgbif> (accessed on 1 April 2020).
81. Conway, J.; Eddelbuettel, D.; Nishiyama, T.; Prayaga, S.K.; Tiffin, N. *RPostgreSQL: R Interface to the 'PostgreSQL' Database System*; R package version 0.6-2; 2017. Available online: <https://CRAN.R-project.org/package=RPostgreSQL> (accessed on 1 April 2020).
82. Wickham, H. *rvest: Easily Harvest (Scrape) Web Pages*; R package version 0.3.5; 2019. Available online: <https://CRAN.R-project.org/package=rvest> (accessed on 1 April 2020).
83. Wickham, H.; Seidel, D. *scales: Scale Functions for Visualization*; R package version 1.1.0; 2019. Available online: <https://CRAN.R-project.org/package=scales> (accessed on 1 April 2020).
84. Chang, W.; Borges Ribeiro, B. *shinydashboard: Create Dashboards with 'Shiny'*; R package version 0.7.1; 2018. Available online: <https://CRAN.R-project.org/package=shinydashboard> (accessed on 1 April 2020).
85. Granjon, D. *shinydashboardPlus: Add More 'AdminLTE2' Components to 'shinydashboard'*; R package version 0.7.0; 2019. Available online: <https://CRAN.R-project.org/package=shinydashboardPlus> (accessed on 1 April 2020).
86. Attali, D. *shinyjs: Easily Improve the User Experience of Your Shiny Apps in Seconds*; R package version 1.0; 2018. Available online: <https://CRAN.R-project.org/package=shinyjs> (accessed on 1 April 2020).
87. Perrier, V.; Meyer, F.; Granjon, D. *shinyWidgets: Custom Inputs Widgets for Shiny*; R package version 0.4.8; 2019. Available online: <https://CRAN.R-project.org/package=shinyWidgets> (accessed on 1 April 2020).
88. Gagolewski, M.; Tartanus, B.; *stringi: Character String Processing Facilities*; R package version 1.4.6; 2020. Available online: <https://CRAN.R-project.org/package=stringi> (accessed on 1 April 2020).
89. Wickham, H. *stringr: Simple, Consistent Wrappers for Common String Operations*; R package version 1.4.0; 2019. Available online: <https://CRAN.R-project.org/package=stringr> (accessed on 1 April 2020).
90. Chamberlain, S.; Szoecs, E.; Foster, Z.; Arendsee, Z. *taxize: Taxonomic Information from Around the Web*; R package version 0.9.7; 2019. Available online: <https://CRAN.R-project.org/package=taxize> (accessed on 1 April 2020).
91. Tennekes, M. *treemap: Treemap Visualization*; R package version 2.4-2; 2017. Available online: <https://CRAN.R-project.org/package=treemap> (accessed on 1 April 2020).
92. Wilkins, D. *treemapify: Draw Treemaps in 'ggplot2'*; R package version 2.5.3; 2019. Available online: <https://CRAN.R-project.org/package=treemapify> (accessed on 1 April 2020).
93. Hiebert, J. *udunits2: Uduunits-2 Bindings for R*; R package version 0.13; 2016. Available online: <https://CRAN.R-project.org/package=udunits2> (accessed on 1 April 2020).
94. Szöcs, E. *webchem: Chemical Information from the Web*. 2020. R package version 0.5.0; 2020. Available online: <https://CRAN.R-project.org/package=webchem> (accessed on 1 April 2020).



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).