TYPE Original Research
PUBLISHED 18 December 2024
DOI 10.3389/fenvs.2024.1406376

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OPEN ACCESS

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RECEIVED 25 March 2024
ACCEPTED 25 November 2024
PUBLISHED 18 December 2024

CITATION
Kusnick J, Lichtenberg S, Wiegreffe D, Huber-Sannwald E, Nehren U and Jänicke S (2024) Visual analysis of diversity and threat status of natural materials for musical instruments.
Front. Environ. Sci. 12:1406376.
doi: 10.3389/fenvs.2024.1406376

Visual analysis of diversity and threat status of natural materials for musical instruments

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A classical symphony orchestra consists of up to 29 musical instruments manufactured from up to 758 distinct natural materials. The interrelationships between the extraction of raw materials for instrument making, the international trade conditions, and the protection status of endangered species and their ecosystems are highly complex and have yet to be sufficiently scientifically examined. However, rapidly progressing climate and ecological change call for sustainable solutions. To address this challenging task, we present *MusEcology*, a new interactive decision support system based on visualizations. The interactive visualizations offer entry points for users of various backgrounds to explore the interrelationships between musical instruments, natural resources and ecosystems. The tool's fundamental objectives are to guarantee that the (1) data processing correlates related data resources, that (2) visual interfaces and interaction schemes encourage new interdisciplinary research on complex systems interactions, and that (3) high-level decision-making is supported to identify alternative pathways towards sustainable instrument making.

KEYWORDS

visualization, musicology, ecology, geography, sustainability, interdisciplinarity, natural materials, threat assessment

1 Introduction

Some of the most famous pieces of classical music are composed for symphony orchestras (Moro, 2019). A symphony orchestra achieves the desired sound only when each musician contributes with their musical instrument in a coordinated and harmonic way. The quality of those musical instruments depends, in turn, on the instrument makers' expert knowledge and skills, but above all on the quality of materials, without which high-standard musical instruments could not be crafted (Zhang, 2012). Thus, manufacturers of musical instruments require access to a large variety of natural materials from animals and plants, especially wood (Fletcher and Rossing, 2012). Following historical European expansion and international trade fueled by the colonial era and ongoing globalization, European musical instrument makers have made use of access and materials from species that originate from distant ecosystems around the world and local environments alike (Moro, 2019). Uncontrolled overexploitation of natural resources worldwide is responsible

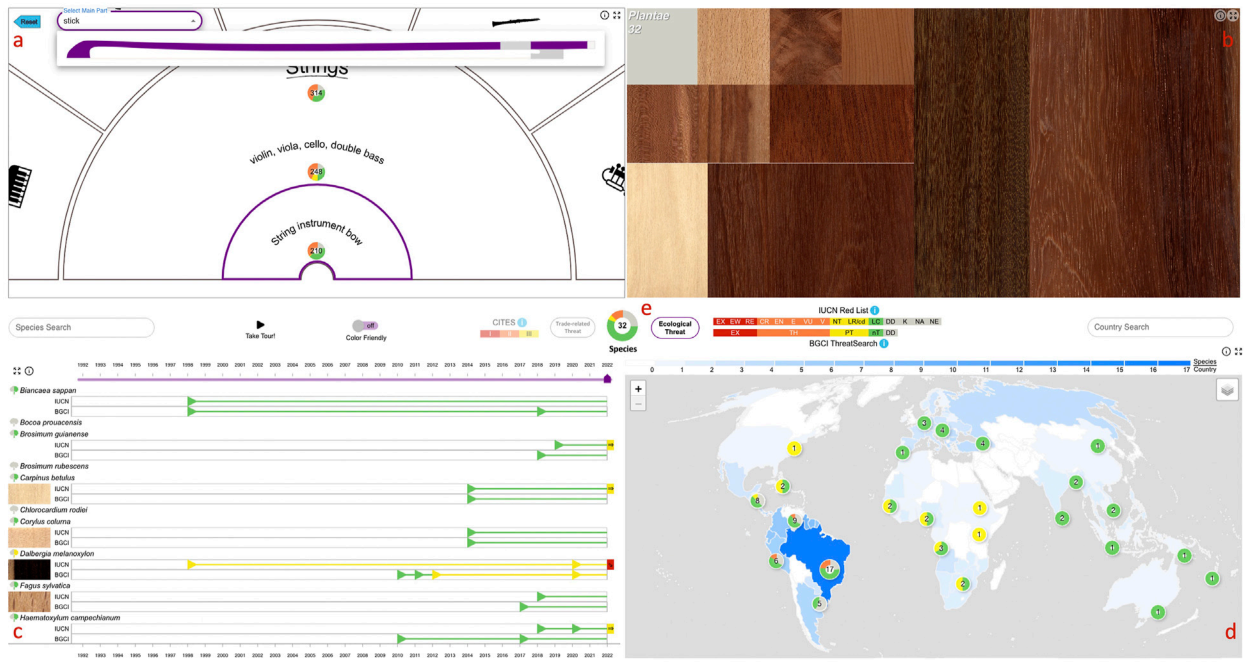

FIGURE 1
MusEcology: Overview of the platform and its interconnected components. The stick of a string instrument bow is selected in the Orchestra View **(A)**. The plant species used to produce the stick are depicted in the Material View **(B)**. Their threat history is contextualized in the Timeline View **(C)**, and the Diversity Map shows their geospatial distribution **(D)**. All the views are connected through a consistent color and glyph design (Legend, Threat Donut, and Threat Icon) and search and filter functionalities **(E)**.

for endangering a multitude of threatened species and ecosystems, increasing the threat to traditional musical instrument making, an intangible cultural heritage that preserves valuable traditional craft knowledge (Heritage Crafts Association, 2021). This precarious ecological situation and cross-cutting culture calls for novel strategies to preserve our "global orchestra ecosystem".

The emergence of global perspectives on the interrelation between nature and music poses a challenge to the preservation of both (Elsasser et al., 2011; Allen et al., 2023). The global loss of significant cultural and natural heritage originates mainly from a profound lack of awareness and understanding of the interlinkage of threats to music, musical instrument making, and distant ecosystems. Research in the field of *ecomusicology* or *ecoorganology* touches some of the mentioned aspects (Allen, 2023). Lichtenberg et al. (2022a) recently proposed an integrative framework to examine these telecoupled cultural-ecological systems from a conceptual and empirical perspective to develop long-term sustainable solutions to this complex challenge. In this manner, the following elements of a holistic system need to be taken into account: materials used for musical instrument making, their highly specific sound characteristics, their visual appearance, the plant and animal species and their habitats, the species' current and historical ecologically grounded threat levels, international trade regulations, as well as their population trends.

Until now, this perspective has in most cases been taken for specific instruments or instrument families and their interconnections to specific species and their threats (Hachmeyer, 2022; Yamada, 2017; Lichtenberg et al., 2022b; Gibson and Warren, 2021; Ryan, 2015a; Allen, 2012).

Our project is the first to tackle these multidimensional interdependencies systematically in visual and interactive form to make them explorable on a meta and micro level. In addition to visualization scholars, our Co-creation Team consisted of a violin maker, geographers, biologists, and an ecologist. The merge of these domain expertise and specific research perspectives set the stage for an overall enhanced understanding of the unexplored interrelationships. Through a participatory and iterative design process (Jänicke et al., 2020), we collectively designed *MusEcology*, a web-based visual analysis platform, addressing the following main objectives:

Visual metaphors to symbolize the ecological and trade-related threat status for single species and sets of them via glyphs (see Figure 1E).

A **linked views design** tailored towards complex data sets with information on musical instruments, natural materials of plant and animal species, their associated threat status, and geographical distributions.

A **multi-layered geospatial design** that allows investigating the distribution of terrestrial and marine species considering political (countries) and ecological boundaries (biomes, ecoregions, approximated species distribution) (see Figure 1D).

A **species timeline** particularly designed to demonstrate the development of ecological threats and trade regulations of species (see Figure 1C).

A **target-user driven design approach** to make the system as a whole accessible and comprehensible for users with a non-technical background (see Figures 1A, B).

We further present two use cases that exemplify the value of the *MusEcology* platform for users of different domains. In addition, we report on informal feedback from domain experts, using *MusEcology*, commenting on its inter- and transdisciplinary potential. Finally, we acknowledge certain limitations and discuss future extensions of the platform.

2 Related work

Our interdisciplinary approach results in a multi-modal set of used resources, data types, and attributes. It calls for appropriate visual representations of individual dimensions and a sophisticated interaction scheme among them to communicate the complex interrelations accordingly. We bear on related works on visualizing hierarchical, temporal, and geospatial metadata and deploy a coordinated views system to allow for a multifaceted exploration of our data set.

Hierarchical Views The taxonomy of the different species in biology is hierarchically organized and forms a tree-like structure. This taxonomy is mostly represented by a tree visualization (Letunic and Bork, 2021; Huson et al., 2007). The treemap is another possibility for the representation of hierarchies (Johnson and Shneiderman, 1999). Thus far, we are unaware of an existing implementation of a treemap used for matching materials to a biological taxonomic classification scheme. However, an approach exists that represents the species hierarchy as a Voronoi treemap (Horn et al., 2009). Also, musical instruments can be classified by a taxonomy. This taxonomy can then be represented interactively as a tree (Dolan, 2017). We also adopt a 180° sunburst chart (Zheng and Sadlo, 2021) that replicates an orchestra's hierarchical arrangement of instruments. Related visual depictions are provided for musical pieces performed by the London Symphony Orchestra (London Symphony Orchestra, 2022) and for the progression of an orchestra's sound (Möller et al., 2015).

Temporal Views The visualization of time-based data is subject to many applications. An overview of different strategies for presenting time series data are discussed by (Aigner et al., 2011). An everyday use of time series is the comparison of attributes over a period of time. Different studies (Heer et al., 2009; Javed et al., 2010; Thudt et al., 2016; Franke et al., 2022) provide recommendations for the visualization depending on the use case. Particular domain-specific usage scenarios of timelines that relate to our focus on threatened species include the CITES Checklist (Centre, W.C.M. on International Trade in Endangered Species of Wild Fauna, C., and Flora, 2001; CITES, 2022) or temporal relationships between musical instruments and musical pieces (Kusnick et al., 2020). Although we lean on the existing design to create some familiarity, we juxtapose diverse information for each species and enhance the visual design with newly created glyphs and icons to combine the different data sets.

Geospatial Views Andrienko and Andrienko (2006) proposed a taxonomy for mechanisms to link multiple displays of geospatial data. An essential aspect of their taxonomy is a "display coordination based on a subset selection", e.g., multiple displays show information about a chosen subset of the data. They are linked by highlighting, zooming, and filtering mechanisms so that an interaction in one display is also reflected in the other displays. If certain areas in the map should represent a particular value, e.g., the population density of a specific species, choropleth maps are often used for the representation (Jänicke et al., 2019; Morgades et al., 2021; Dinerstein et al., 2017). Suppose an artificial grid dividing individual areas hexagons can be used for tiling (McNeill and Hale, 2017), since with hexagons the distance between two tiles can be determined more easily than, for instance, with squares. Furthermore, global forest loss is visualized (Vizzuality, 2022) or the habitats of selected species are presented geographically (The IUCN Red List of Threatened Species, 2022b; Global Biodiversity Information Facility, 2022; Janicki et al., 2016; Telenius, 2011). In addition, Annanias et al. (2022) and Rauer-Zechmeister et al. (2024) have shown how human impacts have reshaped land and in return how climate change is affecting humans in the form of floods. Next to heat maps, Gixhari et al. (2014) designed various glyph-based maps to communicate diverse aspects of fruit tree species distributions in Albania. Reckziegel et al. (2018) discussed the usage of tag maps to display the distribution of tree species that is limited when only using text and color by displaying the most common species in an aggregated spatial area (Ruefenacht et al., 2008).

Multiple Coordinated Views Wang Baldonado et al. (2000) proposed multiple coordinated views to reduce cognitive overhead compared to a more complex single visualization. However, they also note that this approach can impact the training time to use this visualization. We try to reduce this by using visualizations used by the application domain (maps, timelines) and combining them with visualizations we designed specifically for the use case (Material View with veneers and Orchestra View) to lower the hurdles and create entry points into the complex topic. Gleicher (2018) and L'Yi et al. (2021) have also evaluated which approaches to specific use scenarios are recommended for multiple coordinated views. Based on their recommendations, we use a chart-wise juxtaposition, where in the different views, various attributes of the data are displayed for a comprehensive analysis, representing the same set of selected species. This paradigm has also been used to visualize musicology data. For example, Khulusi et al. (2020a) used a combination of timelines, maps, and sunburst representations to connect information on musical instruments and their makers. Moreover, this paradigm is also used to visualize biodiversity data (Barve and Otegui, 2016; Slingsby and Loon, 2013; Jänicke and Scheuermann, 2014). Usually in combination with a map, for example, timeline data and taxonomy of species are displayed in a linked fashion to support understanding of the distribution of birds (Ferreira et al., 2011) or species in the European Red List (Jänicke, 2019).

To our knowledge, we are the first to combine and visually process data from the economic and ecological fields with musicology in a global scale throughout the instruments of a classical symphony orchestra.

Only UNESCO Intangible Cultural Heritage (2022) partially addressed this issue regarding intangible cultural heritages, including traditional musical instrument crafts and their multidimensional threats via an interactive network graph. Ecological factors, such as species threat levels, have a significant impact, among others, on instrument making and need to be brought into context as done for bamboo used for flutes with a scrollytelling on a geo-spatial map by Hachmeyer (2024). For their understanding, necessary visual representations of these interconnections of topics, as well as quantitative meta-information on musical instruments in general, are missing (Khulusi et al., 2020b).

3 Background and task description

Several musical instrument making crafts and musical traditions have been declared Intangible Cultural Heritage by the United Nations Educational, Scientific and Cultural Organization (UNESCO) (Pinto, 2014). At the same time, many natural materials used for making musical instruments originate from animal and plant species (Fletcher and Rossing, 2012) found in natural heritage sites, thus connecting cultural and natural heritage across borders and great distances (Lichtenberg et al., 2022a). To determine and characterize such cultural-ecological interconnections, all instrument parts derived from plants and animals need to be identified at the species level (taxonomically verified) and linked to their natural distribution. A careful selection (type and quality) of these natural materials is essential as this is directly linked to the quality of musical instruments, i.e., referring to critical acoustic, physical, and haptic criteria. Material quality, in turn, is often directly related to geographic location and several biophysical characteristics, such as temperature, precipitation, soil type, and habitat quality. A classification of the origin of species according to such ecological criteria is possible by defining ecological boundaries for areas, taking into account at least one of the boundary characteristics, such as origin and conservation, spatial structure, function, or temporal dynamics (Strayer et al., 2003). Ecoregions define ecological boundaries according to a biogeographic classification system based on the distribution of a range of animal and plant species across the planet and include representative habitats and species communities within biomes (Olson et al., 2001). Biomes describe the global large-scale distribution of ecosystems consisting of different ecoregions encompassing large regions with similar vegetation and climatic conditions (Udvardy, 1975). But also, the visual appearance can influence the value of instruments and confers to the material's uniqueness, rarity, or exoticism.

Since 1964, the "International Union for Conservation of Nature" (IUCN) has been listing species in its Red List and categorizing their threat risk using standardized criteria (The IUCN Red List of Threatened Species, 2022b). The 'Botanic Gardens Conservation International's (BGCI) ThreatSearch' collects similar assessments and provides them on their website (Botanic Gardens Conservation International, 2022b). Species' threats can be considered at and delimited to certain ecosystems, which are classified into biomes and ecoregions (Olson et al., 2001), as well as to socio-economic and socio-political contexts.

Globalization has dramatically contributed to biological and cultural diversity loss, severely impacting human societies (Bridgewater et al., 2007). The main causes of ecosystem loss and degradation are overexploitation of natural resources and land-use change, significantly reducing intact ecosystems, thereby threatening many species worldwide (Foley et al., 2005). For an increasing number of species commercial uses, selective exploitation and international trade pose direct threats to their survival; therefore, trade of these species is regulated internationally (Brémaud et al., 2007; Bennett, 2016) by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). These trade restrictions are necessary but also affect the availability of raw materials for instrument making.

The direct interconnection of cultural and biological diversity through material use for musical instrument making and its reciprocal influence on their common threat becomes apparent in the context of musical instruments and profoundly visible through *MusEcology*. Emerging future challenges for nature and culture are continuous forest loss, land-use changes, and the impact of climate change on ecosystems. These processes together increase the pressure on species used for musical instruments and, consequently, on the musical instrument making crafts and, subsequently, on music traditions.

The visualization of this multidisciplinary, interwoven, complex topic shall support decision-making processes by providing an overview of all described aspects, their interconnections, and certain detailed information resulting in these domain-specific tasks:

T1: Show the importance of music traditions as intangible cultural heritage.

T2 - *mapping*: Establishing overview of the mapping of musical instrument parts (instruments and their instrument groups) to the species used as natural materials.

T3 - *distribution*: Geographically locate the species distribution indicating the number of species per region (species richness) in countries, ecoregions, and hexagons.

T4 - *appearance*: Conveying insight into the visual appearance of natural materials and their biologic taxonomical hierarchy.

T5 - *ecological threat*: Using threat assessments (by IUCN and BGCI) to estimate the ecological threat to each of the species.

T6 - *ecosystem threat*: Inform about threats to ecosystems and biodiversity to evaluate the stress and regeneration potentials.

T7 - *trade*: Reference to trade regulations by CITES as an indicator of pressure on species, trade restrictions for culture, but also as conservation measurement.

T8 - *context*: Providing temporal and geo-spatial context of regulations and threats and population trends to evaluate historical and current status to support future decisions.

4 Methods

The development of *MusEcology* is based on an iterative, participatory design process that encompassed several stages of transdisciplinary elaboration in the form of a nested team model involving six key domains (visible in Figure 2) and their related data sets (see Figure 3). The Core Team designed and implemented the database, visualizations, and web application in form of a design by immersion (Hall et al., 2020). Thereby domain design aspects, supervision, and early feedback were provided through continuous internal evaluation and feedback loops by the experts from the Co-creation Team. We emphasize the balanced gender ratio in these two teams (Core Team, Co-creation Team), whereby further details about the composition of the External Experts are described in subsection 6.2. The collaboration between Core Team, Co-creation Team, and the External Experts followed a participatory visualization design process (Jänicke et al., 2020). Part of this design process was the continuous selection, combination, and new linkages of open-access domain-specific data repositories; this opened new venues to create and visualize unexplored interrelated knowledge and discover new research fields. As a result, our data sets and functionalities keep growing and developing throughout the design process by including expertise via new data sets and project partners.

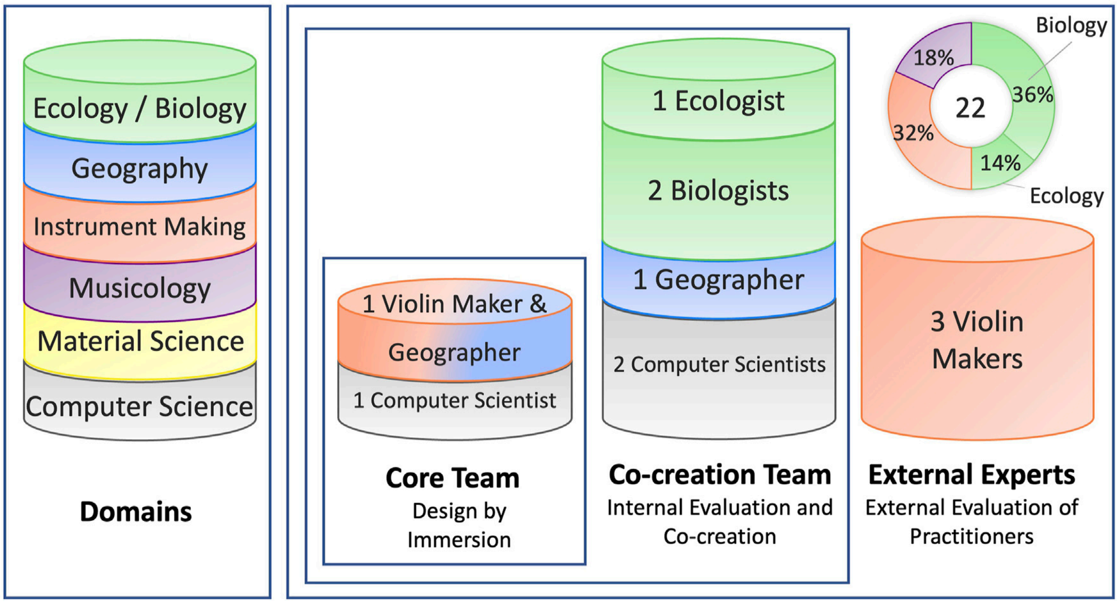

FIGURE 2
With the underlying nested team model, relevant domain experts were incorporated into the participatory visual design process while maintaining the viability of the platform development. Each color-coded slice stands for six key domains and their expert(s): instrument making (red), musicology (purple), ecology/biology (green), geography (blue), material/wood sciences (yellow), and computer sciences (white). All domain experts contributed to the project with data and knowledge from the respective teams.

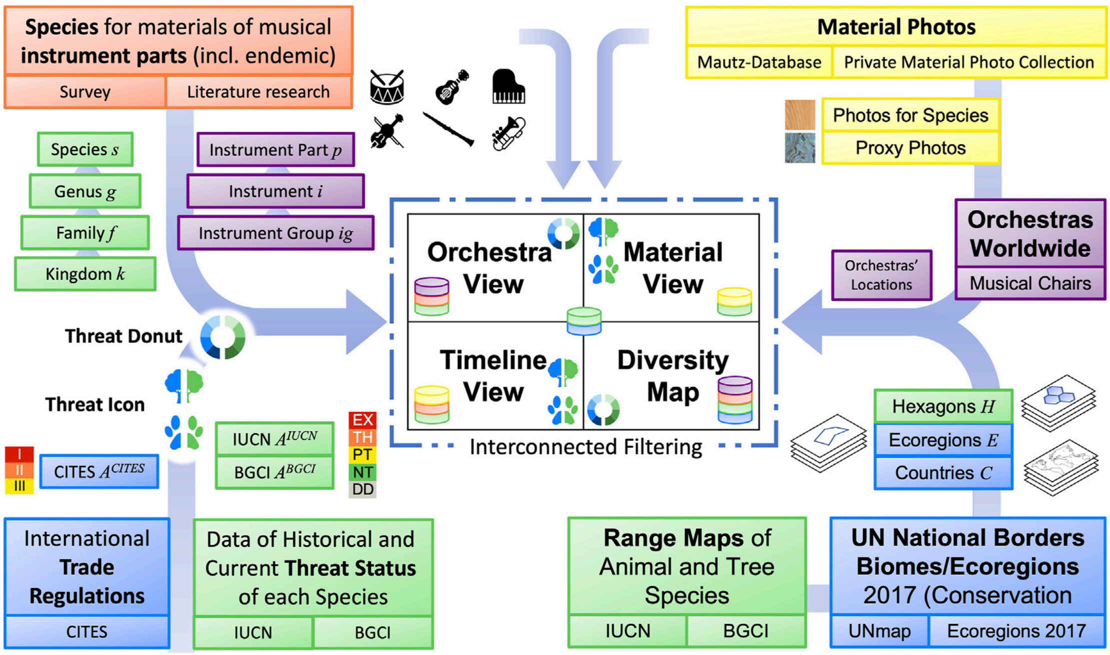

FIGURE 3
An overview of the diverse data repositories linked to our six key domains: musical instrument making (orange), ecology/biology (green), geography (blue), material/wood sciences (yellow), musicology (purple), computer science (white) and merged to depict four different interconnected views: Orchestra, Material, Threat Assessment Timeline, and Diversity Map. This visualizes the transdisciplinary contributions of the mentioned domains and the complex interrelations among the four views representing critical characteristics of a global orchestra ecosystem. The strong connection of ecology and geography to the other domains is symbolized by the use of Threat Icons and Threat Donuts within the visualization views. This tool can answer specific questions of interest related to one or more domains. However, with the visualization of the interlinked views, a novel learning environment can be generated, as well as innovative research questions posed and research gaps discovered.

4.1 Data

To display the complex interconnections described, the incorporated data combines different repositories and sources, which we describe below. For species used for materials to build musical instruments, we used data sources that consider their threat status in an ecological context and an understanding of trade-related restrictions. Regarding both aspects, we focus on the species level by considering political as well as ecological borders as described in Section 4.5 on spatial information. From a biological perspective, the risk of extinction is an important measure to be considered for species used for musical instruments. From an economic perspective, an important measure is the legal trade ability, availability, or scarcity of every natural material used for musical instruments deriving from plant or animal species. Our whole design approach focused on the global level with embedded local processes and foci.The complete **description of species in our data set** is defined in Equation 1:

$$s \in S = \begin{pmatrix} g, & \text{genus} \\ f, & \text{family} \\ k, & \text{kingdom} \\ P, & \text{set of instrument parts} \\ A^{CITES}, & \text{set of CITES assessments} \\ A^{IUCN}, & \text{set of IUCN assessments} \\ A^{BGCI}, & \text{set of BGCI assessments} \\ H, & \text{set of hexagons} \\ E, & \text{set of ecoregions} \\ C, & \text{set of countries} \end{pmatrix} \quad (1)$$

4.2 Materials for musical instruments

We focused on the materials used for musical instruments of symphony orchestras representing the classical music culture. We consulted 17 literature sources in wood and material sciences (Bucur, 2006; Wegst, 2006; Pérez and Marconi, 2018; Bucur, 2016; Bennett, 2016; Wegst et al., 2007; Bucur, 2019; Angyalossy et al., 2005; Brémaud and Poidevin, 2013; Richter, 1988), instrument making and online supplier for parts of instruments (Möckel, 1997; Jahnel, 1981; Paulus Bowparts, 2022; Dullat, 1990), and possible materials used in the case of reference only mentioning a genus or common name (Dullat, 1990; Venkatasamy et al., 2006; Botanic Gardens Conservation International, 2022a) to find out the type(s) of material(s) used for musical instrument parts and the corresponding taxa. We created two major hierarchically structured data sets as the foundation.

The first is a nested hierarchy based on the following assumption that an orchestra O can be divided into:(1) Multiple instrument groups IG, therefore, applies $O = \{ig \in IG\}$, where (2) an instrument group consists of instruments I with shared characteristics $ig = \{i \in I\}$, and (3) an instrument is built of instrument parts P, described as $i = \{p \in P\}$. Specifically, instrument groups of an orchestra are $ig \in \{Strings, Keyboard, Plucked, Woodwinds, \; Percussion, Brasses\}$. In addition to the typical orchestra instruments, we considered the guitar, bagpipe, cembalo, and recorder family to include other popular musical instruments.

The second domain set relates to the natural materials used to manufacture musical instruments. We created a database linking instrument parts of each musical instrument and the species origin of materials used, so that the instrument parts are defined by several species $s(P) = P = \{s \in S\}$. Species are the lowest level of a biological taxonomic system that we are considering; thus, it has a clear assignment to a genus $s(g) = g \in G$, family $s(f) = f \in F$, and kingdom $s(k) = k \in \{Animalia, Plantae\}$. We can use the above-listed assumption recursively so that the instrument group is also “consisting” of species $IG = \{I\} = \{P\} = \{S\}$.

In total, our database includes 5,965 assignments for six musical instrument groups, 39 musical instruments, and 65 different main parts of musical instruments; they are assigned to 758 species (60 animals and 698 plant species), 286 genera, and 113 families. We merged instrument families and musical instruments made of the same components into a single group if the same materials can be used for their construction, such as all string instruments, while, e.g., the string instrument bow is listed separately as its own instrument, because it consists of different parts and materials than string instruments. The database by Silke Lichtenberg can be found online under https://zenodo.org/records/10546544.

4.3 Species threats

Different assessments exist for animal and plant species that determine the risk of species extinction on a global scale. Independent of this, but taking this risk into account and depending on the cause of the threat and political interests, decisions are made on necessary trade regulations and the extent of restrictions to prevent their extinction.

The threat state, or the extinction risk of each species at a global level, is scientifically assessed and then published. Our decision support system can be described by a tuple of necessary information specifying the assessed category of threat state a_c and the publication year a_y; for now, we are only focusing on global assessments. So, the set of all historical and most current assessments of a species s can be noted as $s(A^*) = \{(a_c, a_y)\}$. Whereby A^* stands for a set of assessments from one source $\in \{CITES, IUCN, BGCI\}$, which are described in the following sections.

4.3.1 Ecological threats

The IUCN Red List provides information on the range, population size and trend, habitat and ecology, use or trade, threats, and conservation actions and indicates the health of the world’s biodiversity (The IUCN Red List of Threatened Species, 2022b).

However, other assessments of global scope evaluate species similarly and categorize their threat risk. The “BGCI ThreatSearch” collects these different assessments for plant species, including those of the IUCN Red List (Botanic Gardens Conservation International, 2022b). For each species used for musical instruments, we identified the respective species-specific threat status considering the listings of the database of the IUCN Red List and the listings in the BGCI ThreatSearch as well as their changes in threat status at the global level over time, creating the sets $s(A^{IUCN})$ and $s(A^{BGCI})$.

Although both repositories use their categories to describe the threat levels, they stay comparable by the BGCI ThreatSearch mapping (Botanic Gardens Conservation International, 2022b). For example, “Possibly Threatened” (PT) is mapped to both IUCN Red List categories “Near Threatened” (NT) and “Lower

Risk/Conservation Dependent" (LR/cd). Thanks to this system, the various categories are also sort-able so that we can decide on the strictest BGCI ThreatSearch assessment because there can be multiple listings in 1 year $strictest\,(s\,(A^{BGCI})) = argmax\; s\,(A^{BGCI})$.

To obtain one summarizing statement for the ecological threat of species, we group the assessments of the IUCN Red List and BGCI ThreatSearch and decide according to the following procedure. The assessments by the IUCN Red List are the most widely used sources internationally and are included in the BGCI ThreatSearch. We use the *latest* IUCN listing and the *latest* assessment of ThreatSearch if the specis in not listed in IUCN, as noted in Equation 2. Taking the example of *Manilkara longifolia* at the global scope, in 1998, it was listed as "endangered" in the IUCN Red List; in 2011, BGCI ThreatSearch shows its listing as "not threatened", which would be the *latest* listing. But as we prioritize the IUCN Red List listing, we depict the summed threat as "endangered".

$$s\,(threat) = \begin{cases} latest\,(s\,(A^{IUCN})), & \text{if } |s\,(A^{IUCN})| > 0 \\ strictest\,(latest\,(s\,(A^{BGCI}))), & \text{otherwise} \end{cases} \quad (2)$$

4.3.2 Trade-related restrictions

At the global scale, regulation of trade between countries and across continents of materials from endangered species is of utmost importance and the task of CITES. The agreements on trade restrictions decided by CITES are legally established and implemented by each member state; they are based on the findings that economic trade of the species in question contributes significantly to its threat. Therefore, for the trade-related threat, we considered the species-specific listings in CITES by consulting the Species + database (Centre, W.C.M. on International Trade in Endangered Species of Wild Fauna, C., and Flora, 2001) and their changes over time $s\,(A^{CITES})$. Whereby the *latest* CITES listing in history is the actual state of trade regulations in our system, as described by Equation 3:

$$s\,(trade) = latest\,(s\,(A^{CITES})) \quad (3)$$

4.4 Materials' appearance

Visual criteria are essential for distinguishing materials and play an important role in selecting materials for musical instruments. The material appearance of tree species is made accessible by 174 assigned photos of the extraordinary Mautz wood collection of the Thünen Institute Hamburg and 35 photos of animal and plant species derived from the personal photo collection of Silke Lichtenberg. All photos are linked to the respective species in the database of materials of musical instruments. For species without existing photos in the collections, we manually selected similar-looking species' material within the same genus as a proxy photo of the available images.

4.5 Spatial information

We are interested in spatial information available in different data types to give insight into the global diversity and distribution of species used for musical instruments. We received point distribution data sets for 360 tree species from the "Botanic Gardens Conservation International" (BGCI) (Botanic Gardens Conservation International, 2022a). Additionally, we downloaded 28 available animal species distribution maps from the International Union for Conservation of Nature and Natural Resources (IUCN) Red List webpage (The IUCN Red List of Threatened Species, 2022b). To cluster and homogenize these distribution maps for all species, we binned the point datasets of BGCI and intersected the polygon datasets of the IUCN Red List to an artificial global hexagon raster, where each hexagon corresponds to approximately 1,000 km^2 $s\,(H) = \{h\}$. To create an ecological habitat understanding, we embedded the species distribution to terrestrial ecoregions $s\,(E) = \{e\}$ (Dinerstein et al., 2017).

As international trade regulations are implemented at a country level, we used the countries listed for each species in the BGCI TreeSearch (Botanic Gardens Conservation International, 2022a) as well as the countries listed in the IUCN Red List database to map species richness at the country level $s\,(C) = \{c\}$. We synchronized the given country names with the country borders published by the United Nations (UN) (Humanitarian Data Exchange, 2022).

5 Visual design

In this section, we explain our visual design approach for the visualization of the collected and combined interdisciplinary data repositories by starting with a description of how they were merged and which domains are addressed in which part of the visualization, as well as a description of which design decisions were taken and why. We continue describing the assumptions, aggregations, and interactions to the details of specific visualization elements.

The result of this process was *MusEcology*, a web application using JavaScript libraries such as React (React, 2022) for the overall architecture, Leaflet for the map, and D3.js (D3.js, 2022; Bostock et al., 2011) for other visualization components, forming four interactive and interconnected views that offer an intuitive entry point for users of different disciplines opening up insights into them, as schematically shown in Figure 3. The tool and its code can be found online here: https://github.com/Vokabelsalat/musecology.

5.1 System design

The desire to include **Interconnected Filtering** throughout *MusEcology* as the core of our design originates from the goal of this application, intended to strengthen the complex system's understanding, where all elements are connected and by changing one aspect in the system all other factors are directly or indirectly influenced. Each visualization view can be accessed and used to explore and analyze various topics. They are linked by reoccurring visual elements as summarizing glyphs: the **Threat Icon** of the pressure on single species (**T5, T7**) and the **Threat Donut** encoding status overviews of sets of threatened species (**T5, T7**).

5.1.1 Interconnected Filtering

All visualizations are based on a set of species, and they are generated through a faceted filter process defined by user

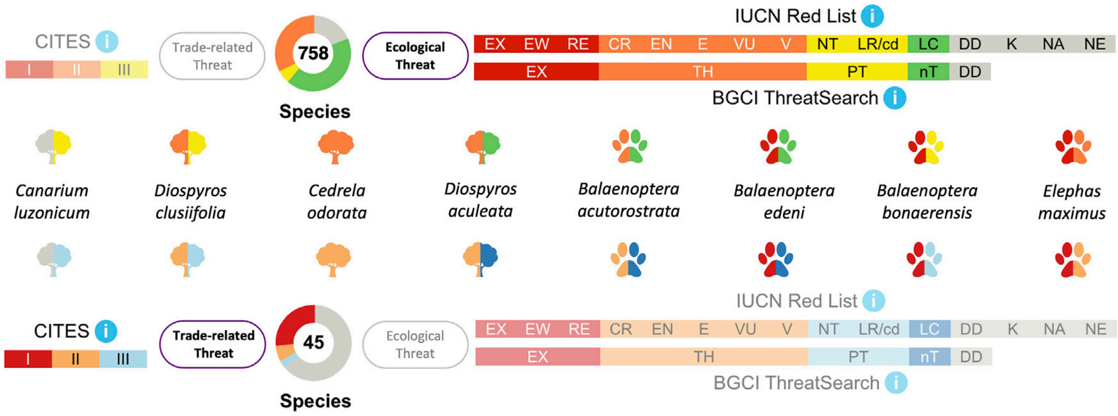

FIGURE 4
The top two rows show the species glyphs (Threat Donut and Threat Icon) and color legends in default color mode, and the bottom two rows are in color-blind friendly mode. The traffic light color-coding for the categories of the IUCN Red List, BGCI Threat Search species assessments, and CITES listings is explained by the Color Legends. Threat Donut: The Threat Donut is a central part of the legend and is depicted in the orchestra view and the diversity maps. It always symbolizes the combined threat (trade-related or ecological) of all species in the current selection for either. It depicts the most recent ecological or trade-related threat assessments for selected species. The aggregating Threat Donuts show the overall threat distribution considering the number of species in the selection (e.g., instrument group, instrument, country or taxonomic group, etc.), either related to trade-related restrictions/threats or ecological threats (see purple framed legend labeling). The Threat Donut on top represents the ecological threats of all 758 species, and the bottom encodes the trade-related threat/restrictions for selected 45 species. Threat icons: the Threat Icon (the two middle rows) is only depicted on a species-specific level, not for a group of selected species, and always shows the trade-related threat linked to CITES on the left and the ecological threat on the right.

interactions considering all four visualization views and other user interface elements. Clicking an interactive element activates the faceted filtering regarding the corresponding data dimension, and the rest of the interface updates accordingly because the filter is applied in all views on the overall used resulting species subset. Thanks to the described variety of data dimensions of one species s, we allow the intersected filtering by:

(1) Biological taxonomy $(s(name), s(g), s(f), s(k))$,

(2) Use in the orchestra $(s(P), s(I), s(IG))$,

(3) Geospatial distribution $(s(C), s(E))$ and.(4) Threat level $(s(A^{IUCN}), s(A^{BGCI}), s(A^{CITES}))$.

The application then filters the species set according to the selected attribute values where the conjunction of all filter settings is used. The selections within the views are highlighted by outlines in a purple color like shown in Figures 1, 5, 6 because this color is not used in the rest of our color pallet.

5.1.2 Threat Icon

The design decision for a threat icon that appears in the different views originated from the feedback of the domain experts pointing out the gain of information when including one single threat icon that easily allows the classification of the threat situation (**T5**, **T7**). During the process of trying to implement such an icon, we detected that it is not possible to transparently combine trade-related restrictions and threats (CITES Trade regulations) and ecological threats (IUCN Red List/BGCI ThreatSearch) in one icon without losing the original information of the data repositories. Therefore, we developed the two-part tree and paw Threat Icons presented in Figure 4. It combines trade-related threats $(s(trade))$ on the left half and ecological threats $(s(threat))$ on the right half and symbolizes with its coloring the most recent threat levels. Without an assessment, we symbolize the missing knowledge by the gray color for "Data Deficient". A tool-tip explains this compound threat icon when users move the mouse cursor over a Threat Icon in the Timeline or Material View.

The coloring for assessments in our visualizations is derived from the color pallet used by the IUCN Red List for their assessment categories. Whereby we color-matched the categorizations of the IUCN Red List and BGCI ThreatSearch according to BGCI ThreatSearch mapping, as described in subsubsection 4.3.1 and shown in Figure 4. The color coding for the CITES listings follows an analog logic: the stricter the regulations, the more threatened the species must be by trade, and the more significant the potential negative impact or threats to the traditional craftsmanship of musical instrument making due to materials scarcity. As our traffic light colors for the various threat levels are significantly based on the contrast of red and green, we enabled an optional color pallet through an interface switch for a more color-blind friendly mode with the use of ColorBrewer (Harrower and Brewer, 2003).

5.1.3 Threat Donut

By using the most recent states of the Threat Icons, we can derive a glyph for a whole set of species $(\{s_n\})$ as an aggregation in our interface. During our iterative process, we discovered that a one-colored icon of hierarchically upper levels, such as instrument groups or countries, would oversimplify the complexity and lead to unjustified generalizations regarding the selected species' threat status. To address this problem visually, we decided to use a donut chart showing the distribution of different threat levels by colored ring segments and the number of species $(n = |s_n|)$ depicted in the center of the screen to show an estimation of the whole current selected set of species. For example, we can draw the ring segment for the occurrences of Appendix I listings by CITES of all the species in our scope (n) by using its cardinality as measurement for the size and the mapped color (in this case red) $(|\cup_{i=1}^{n}\{a \in s_i(trade)|s_i(trade)_c = \text{Appendix I}\}|)$. We are using a

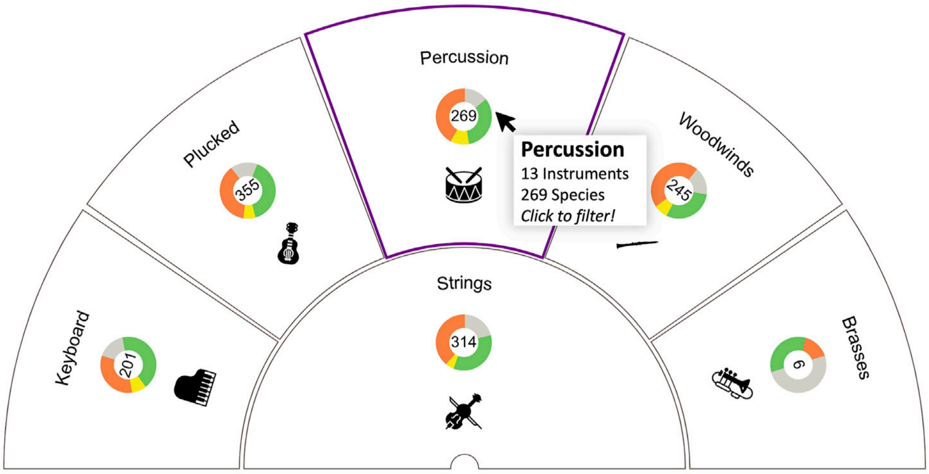

FIGURE 5
Outlines in purple highlight the selection of an instrument group within the Orchestra View. Each instrument group is symbolized by a slice within the schematic orchestra and a musical instrument icon to enable the visual entry point into the nested hierarchy of instruments and their parts. The ecological or trade-related Threat Donut inside each orchestra slice refers to the average threat status of the total number of species used for a particular instrument group.

FIGURE 6
Left: Detailed view of the wood appearance of *Paubrasilia echinata* with the table indicating the selected kingdom, family, genus, and species. Left: map with *Paubrasilia echinata's* hexagon distribution along the coast of Brazil. The tree Threat Icon entirely in orange indicates the trade-related threat (left half) - a listing in CITES Appendix II - and the ecological threat (right half) - being a species categorized as endangered. The orange Threat Donuts in the map indicate with the number 1 that only one species is selected and depicted in the hexagons - (*Paubrasilia echinata*) - which is endangered and listed in CITES Appendix II, depending on the chosen mode (trade-related threat or ecological threat).

switchable mode to either focus on trade-related threats (**T7**) or on ecological threats (**T5**), allowing to change between two different appearances of each Threat Donut. We pick up the Threat Donuts in our Orchestra View (see Figure 5) to depict the threat level distribution and the number of species used for single instrument groups (**T2**). We also convey the threat information to geographical regions (**T3, T8**) in the Threat and Diversity map (see Figure 6).

5.2 Visualization views

Since the combination of the complementary, equally important information and all interconnections among them build the core of the *MusEcology* platform, we decided to divide the monitor into four equal-sized visualization views, including: a schematic **Orchestra View** of natural materials used for musical instruments in an orchestra, the **Material View** treemap displaying the taxonomy and visual appearance of them, the geospatial distribution in the **Diversity and Threat Map** and temporal progression of species threats in the **Timeline View**.

5.2.1 Orchestra View

For the world of musical instruments, the symphony orchestra is our scope, thus we chose a schematic structure of a simplified classical orchestra with instrument groups organized around the conductor and its underlying hierarchy as described in Section 4.2.

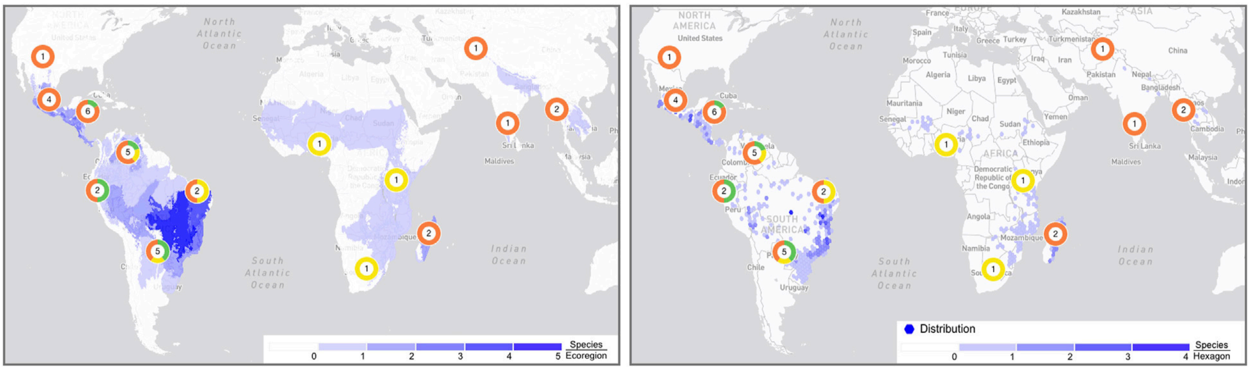

FIGURE 7
Two maps in comparison to show the difference between ecoregions and hexagon map. Left: The ecoregions of the *Dalbergia* species explicitly listed in the literature for the use of guitar backs and sides. Right: The same species' distribution in hexagons reveals that the species do not occur in the entire ecoregions and their species-specific distributions cover a much smaller area.

We decided for a domain specific design although it creates substantial whitespace compared to other selection methods. We want to lower the hurdles and enable experts of domains such as instrument making or musicology to find recognizable symbolics as entry points into the system and complex topic, and since the symphony orchestra symbolically represents the classical music world (**T1**) it arouses curiosity from users of disciplines not connected to music. We present instrument groups by matching icons and symbolize the summary of used species within the groups (**T2**) by their diversity of threat levels (**T5, T7**) in form of the switchable Threat Donuts (see Figure 5). Thereby the set of species within an instrument group is $\{s_i\} = \{P\} \in \{I\} \in \{IG\}$. Clicking on individual instrument groups zooms in (also in the viewport), filters the dataset for species used in this instrument group and reveals the underlying instrument list (see Figure 1A). Within the list of instruments, it is also possible to focus on one single instrument by clicking, and a selector for the underlying instrument parts appears. In contrast, neighboring instrument groups remain visible in the zoom viewport. Suppose a schematic construction plan of an instrument is available in our database. In that case, users can visually select the instrument part instead of the textual selection in the dropdown menu as shown for the string instrument bow in Figure 1A.

5.2.2 Material View

Including a view focusing on the natural materials used for musical instruments and their visual appearance (**T2**) allows us to link them with ecosystems from which the species stem. We make these central elements and their appearance (**T4**) directly visible while highlighting their taxonomic rank by showing their photos within a zoomable, rectangular treemap. Similarly to the Orchestra View, this view contains all species in the actual selection. It follows in its zoom levels the hierarchical taxonomic classification system as described in Section 4.2. For example, the default and most coarse level of the Material View is created by the division of species in their kingdoms, either animals or plants $s(k) = k \in \{Animalia, Plantae\}$ including corresponding family, genus and species sub-groups. The size of each group rectangle is defined by the number of the species in it $|s \in k|$. We also use cardinality for sorting the groups, so neighboring cells in the Material View are not phylogenetically closest to each other. Whereby we prioritize the entries with lower amounts of species to the top left because, during our evaluation rounds, we experienced that these sets of species were overlooked at the utmost right edge of the screen. A preview of the underlying next zoom level is shown in one group rectangle. Thereby, each sub-group is symbolized just by the photo of the predominant, the most common species, to avoid visual clutter. A click on each group is zooming in and filtering the whole set of species accordingly across the entire system. On top of the Material View, we indicate the actual selection within the hierarchy by a table, stating kingdom, family, genus, and species (see Figure 6), which are also used to move up in the hierarchy again by clicking. When single species are apparent, like in the case of the genus or species group overview, the matching species Threat Icons (**T5, T7**) are annotated in the bottom left corner of the rectangles (see Figure 6). But we decided against an overlay of threat pies within the Material View itself to keep the view free of further distractions. The proxy photos for species without an actual image are distinguished through a semi-transparent gray overlay and the text "proxy" on top of it. For users who wish to directly access the information of certain species, we also implemented a search bar for single species and genera, which filters the species directly for names.

5.2.3 Diversity and Threat Map

The species richness and threat map is a central part depicting all interconnections in a spatial context to quickly locate the distributions of species–the origins of materials used for musical instruments within different kinds of regions. Our map's regions can be countries (see Figure 1D), terrestrial ecoregions (see Figure 7 **left**), or hexagons (see Figure 7 **right**), depending on the selected semantic zoom level. To show the richness and spatial distribution (**T3**) of the selected species, we map the number of species in regions on an interactive and zoomable choropleth map. For example, the diversity in a country c is given by the different species found there $(|\{s \in S | c \in s(C)\}|)$, and can be symbolized by the underlying blue intensity (heat map), the more intense the color, the more species appear in that polygon. The regions are also connected to the trade-related restrictions (**T7**) and the ecological threat status (**T5**)

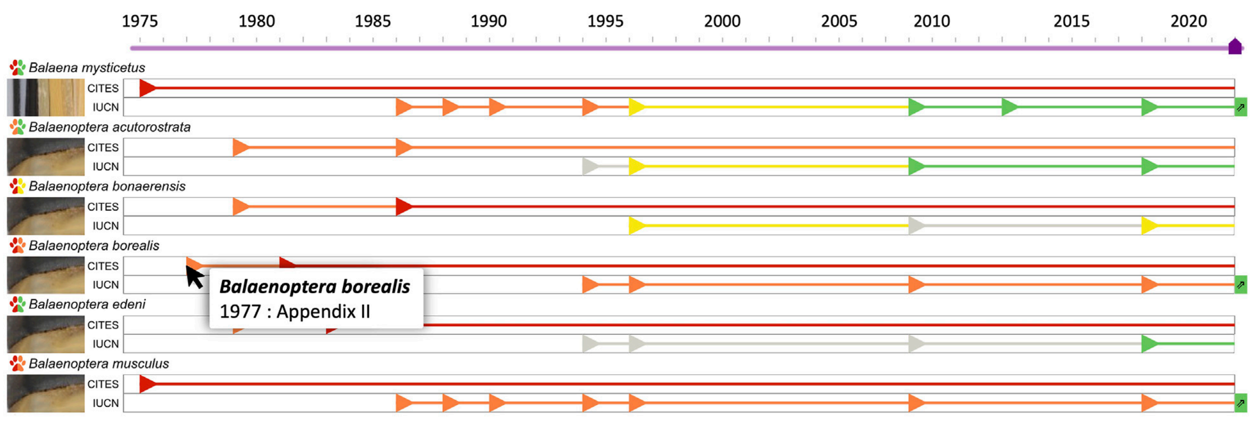

FIGURE 8
Detail of timeline of the 40 animal species used for string instrument bows, with focus on baleen whales whose trade, of whalebone, among others, used for the grip of bows, has been restricted since the 1970s. The purple time-slider helps to filter for time and therefore allows to animate the progression throughout time within all of the other visualizations. Hovering over one assessment with the mouse reveals more details.

by overlaying Threat Donut charts (**T8**). The combined visualization of species richness and threat level captures elements also determined for the earlier mentioned biodiversity hotspots (**T6**), although in our case, limited to species used for musical instruments occurring per country, ecoregion, or hexagon. The placement of Threat Donuts within the map corresponds to the country level, the location of the countries, capitals, and, in the cases of ecoregions and hexagons at the geometrical center of the ecoregions. The clustering of the donut charts is implemented by an extension (Leaflet.markercluster—Marker Clustering plugin for Leaflet, 2022) to avoid overlap by grouping neighboring Threat Donuts and merging their existing species. Framing of the areas clustered in a donut chart is revealed through a mouse hover using the purple highlight color for the bordering lines. We decided on the Mollweide projection, being a good compromise between an equal-area projection to adequately represent the Global South and to meet the aim of an appealing map design, consistent with the findings of (Leon et al., 2008). Depending on the mode of the map, the users can search for countries, ecoregions, and their associated biomes by name. At the same time, they are supported by autocomplete recommendations to facilitate a fast target-oriented use of *MusEcology* via the search bar.An additional layer of the map does not follow all design decisions but complements the Orchestra View, focused on the musical instruments and their parts, by showing the distribution of classical orchestras (with all their instruments) worldwide by their geolocation which opens another perspective for the musicology domain (**T1**).

This orchestra distribution layer in combination with the species richness maps illustrates the understanding of a meta-coupled cultural-ecological system. All orchestras are embedded in different local ecosystems through their locations around the world and are interconnected through the materials used for their instruments (**T2**), which are sourced from various species from diverse ecosystems around the globe. Here, the donut charts are filled by the purple highlight color, and the diversity heat map in the background encodes the number of orchestras per country in blue shades (Figure 9).The second additional map layer is the "Ecoregion Protection Potential" showing a future perspective on the potential of each ecoregion for reaching half of its area being or becoming a protected area (**T6**), which is based on the results of Dinerstein et al. (2017). Increasing the size and number of protected areas is considered an essential strategy to preserve biodiversity, counteract the mass extinction of species, and contribute to climate change mitigation. We are reusing the polygon layer of ecoregions to unveil their potential to be protected by color coding corresponding to our color map of threat levels (see Figure 9).

5.2.4 Timeline View

The investigation of historical and present threat assessments originates from a complex system's understanding; it assumes that to determine the current situation, it is necessary to consider past developments and changes to estimate future effects (**T8**). To communicate these changes in threat status over time, we developed a Timeline View, listing every species' ($s_i \in \{s_1, \ldots, s_n\}$) threat development in a single row. Whereby we introduce the row of s_i by a thumbnail image of the material to convey a first impression of the visual appearance (**T4**), visible in Figure 8. In the following, the history of all available listings of the species is divided into sub-rows (**T5, T7**) regarding their source ($a \in s(A^{*}) = \{s(A^{CITES}) \cup s(A^{IUCN}) \cup s(A^{BGCI})\}$). Due to the diversity of their processes and assertions, we decided against aggregating the assessment throughout the three repositories at this place and chose a juxtaposition. Since the assessments are done at a certain point in time, they can explicitly reflect the actual status only in the assessment year (a_y). The uncertainty about the subsequent dynamics is why the individual assessments are symbolized by triangular glyphs pointing to the right, located in the timeline according to the year of the publication (see Figure 8). Until a new assessment is made, the threat status is depicted by a line showing that the last historical assessment remains the reference for the species. However, its accuracy was only assured in the year of publication.

We use tool-tips in the timeline revealing the details by hovering over the single assessments arrow glyphs or the population trend at the end of the IUCN Red List's sub-row. This population trend is assessed by the IUCN Red List (The IUCN Red List of Threatened

Species, 2022a) and is used by us for reasons of accuracy and to counteract false interpretations of the previous assessments (**T8**). We use the same traffic light color coding for the four possible states: increasing, decreasing, stable, and unknown.

Through the time-slider above, the upper border of the actual species threat status reflection can be set, so that the assessments are filterable by this upper border of the time frame to display the *latest* states in a decent historical point in time. For example, with the year filter set, the following applies to CITES: The trade (left) part of the Threat Icon, according to the last CITES listing before a given year *i* is described by Equation 4:

$$s\left(trade_{y=i}\right) = latest\left(\left\{a \in s\left(A^{CITES}\right) | a_y < i\right\}\right). \quad (4)$$

We decided on a one-sided slider, just filtering at the upper border of the time frame because the last assessment in history is determining the actual status, which is also indicated by *latest* in our formulas. The assessments after the selected year are still visible but grayed out, and the species icon is adjusting accordingly to the last assessed states within the time frame. By moving the slider, the user can also inspect the historical development of threat states in other visualizations, where aggregations such as the recurring species Threat Icons in the Material View are also updated according to the selected time frame.

In conclusion, the interactive exploration and search with the coupled, updating views support the discovery of interconnections in a user-driven way to make sense of the topics and interdependencies, because the tool can be configured to visualize any interconnection between an arbitrary region and its species on the one side, and an instrument on the other, all in context of ecological- and trade-related threats throughout time.

6 Discussion

Designing a platform for multidisciplinary user groups of very distinct backgrounds implies the challenge of combining this different information that only scratches the surface and possibilities to dive deeper into the topic while remaining understandable and approachable for non-experts. For today's complex challenges, however, a holistic understanding of interrelationships, including aspects not usually considered, is becoming increasingly important. Therefore, transdisciplinary projects involving domains that rarely cooperate hold high potential to identify comprehensive entry points for addressing these complex challenges, as the following use case by instrument makers tries to emphasize and an additional second use case (see Appendix) on the variety of Malagasy Ebony by geographers underscoring the potential of MusEcology.

6.1 Use case: pau-brasil bow stick

For experts in musical instrument making and musicology, the initial focus and interest is on the orchestra and the search for details of groups of instruments - in this case, string instruments. As depicted in Figure 1, the separated listing of a string instrument bow as an own instrument and the relatively high number (210) of potential species used for making them, as well as the high ratio of trade-regulated species, is eye-catching and triggers the user to explore the details for string instrument bows further. Through the former selection, the Material View updates, and the user realizes that 170 materials are of plant origin and 40 are of animal origin. Hovering over the assessments of the listings in the timeline, one notes that the trade in whalebone, which was once used for the thumb leather to protect the handle of a bow, has been strictly regulated or even banned for all baleen whales since the late 1970s (see Figure 8).

When switching over to the plant species of the Material View, the overview of ecological threats of species strengthens the impression that many materials face ecological difficulties and that the trade of these materials is possibly contributing to that situation. When selecting the stick as the essential component of a string instrument bow, it becomes apparent that most of these species come from Brazil, and not many come from other tropical regions/countries; only four European species are potentially used. This triggers the user's interest to explore only potential Brazilian species on the map. The photographs in the Material View allow the user to recognize that wood appearance differs slightly between the used materials; this aspect by itself is interesting since the optical appearance of an instrument plays a vital role in its acceptance by musical instrument makers and musicians. Two species exhibit a decreasing population trend, and in 1998 - when monitoring population trends did not seem common yet, three species were listed as endangered. This suggests to expert users of the biology/ecology domain to consider the ecosystem's conservation state to place the information of the species in the overall context. However, scrolling down the species listed in the timeline, the users notice that only one species, *Paubrasilia echinata*, is listed in CITES and faces trade restrictions. With expert domain knowledge of musical instrument making or musicology, it turns out that *Paubrasilia echinata*, commonly known as pau-brasil, is the raw material high-quality string instrument bow sticks are primarily made of. This species is listed as endangered and since 2007 in CITES Appendix II. Zooming to that species and switching to the hexagon scale of the map, the user can get an impression of the range map with its occurrence mainly at the coast of Brazil in Figure 6, where the Material View also gives an impression of the wood appearance of *Paubrasilia echinata*. When reviewing the related ecoregions, experts from ecology and geography can confirm that the species only occurs in the *Mata Atlântica*, one of the 25 biodiversity hotspots worldwide. But non-domain experts can also get an idea of the ecoregions threat. Through the "Ecoregion Protection Potential" map layer, it can directly be identified that all ecoregions of pau-brasil occurrence are either in the category of "imperiled" or "could recover" indicating for the most significant part of the distribution area the severe situation of the species (see Figure 9).

6.2 Evaluation

Developing the different elements of *MusEcology* was a continuous process in the core team. At the same time, its applicability was regularly tested and evaluated by sharing key development steps with the Co-creation Team. We included a two-step approach for further

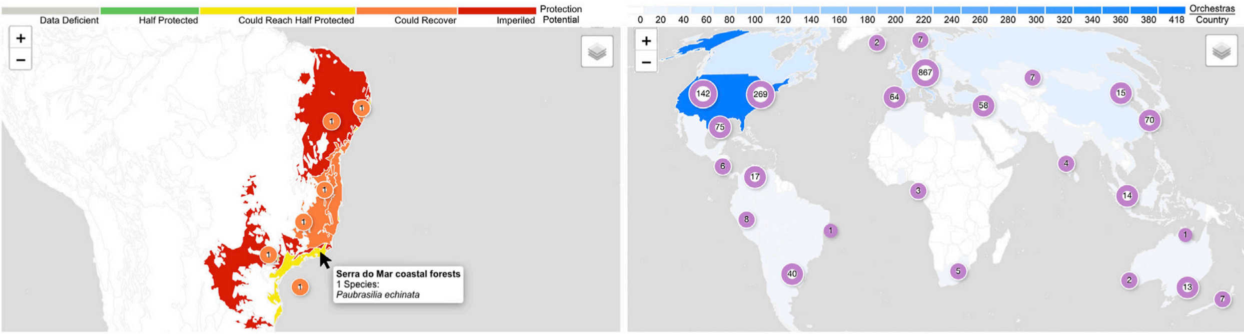

FIGURE 9
Left: Detailed view of the potentials for protecting half of the ecoregions with occurrences of *Paubrasilia echinata* showing in the tool-tip the category "could reach half" (yellow) for the ecoregion "Serra do Mar coastal forests" and its potential for protecting half. Right: Worldwide distribution of symphony orchestras, shown by color-coded occurrences within country borders and purple "Threat" Donuts.

TABLE 1 Visualizing this multidisciplinary, interwoven, complex topic shall support decision-making processes by providing an overview of all described aspects, their interconnections, and specific detailed information resulting in these domain-specific tasks. According to the questionnaire 81% of the participants felt satisfied (S5 rating ≥ 5) with the support by *MusEcology* in order to achieve the goals of their chosen scenario(s).

Scenario	N
Musical Instrument of Interest: Explore the 'Orchestra View' with its different instrument groups and the underlying musical instruments to find your musical instrument of interest and discover the musical instrument parts it consists of (**T2**). Observe the distribution of the used materials in the Diversity and Threat Map (**T3**) and their variety of appearances in the material view (**T4**). Switch between trade-related threat (**T5**), and ecological threat (**T7**) to observe the differences. Scan the timeline to find out about the history of these listings (**T8**). What is your impression regarding the current threat to your musical instrument (**T1**)?	16
Region of Interest: Explore the region you are most interested in and perceive the changes occurring in the other views when selecting (**T3**). Consider the different available scales (countries, ecoregions and hexagons as well as the protection potential (**T6**)) to find out more about the species richness and division of the threats. Switch between trade-related threat (**T5**) and ecological threat (**T7**) to observe the differences. What musical instrument groups require most species from the region of your interest (**T2**)? Which species are most threatened (Timeline View) (**T8**)?	12
Material of Interest: Explore the material view and focus on a visual appearance you are interested in (**T4**). Perceive the material clusters and discover the zoom levels offered down to the species level. Observe how the other views change according to your selections (**T2**). As a guide you can use what catches most of your attention or what taxonomic group you are most interested in. Find out about the geographical distribution of your selected material in the Map View (**T3**). How ecologically threatened or threatened by trade was the material over time (**T5,T7,T8**)? For which instruments is your material of interest used for (Orchestra View) (**T2**)?	8

improvements through external experts to expand this internal evaluation process. First, we shared the tool with three musical instrument makers and the Co-creation Team, who tested an intermediate pilot version, which entailed a further iteration to improve the platform. Considering the most urgent issues raised, we implemented fullscreen buttons to enlarge only one of the four main views to identify certain details; we recorded a video tutorial to introduce the concept and principal components of *MusEcology*, realigned and improved the switch between trade-related and ecological threats, and enabled the search for biomes and ecoregions. Already there, the experts highlighted the unconventional combination of information and innovative insights on interconnections, which for the first time clearly showed that the high number of plant and animal species used for musical instruments are distributed around the globe. For them, it became clear that this complementary cross-disciplinary information allows for a profound understanding of the complexity of the big picture and assists decision-makers at the local, national, and international levels. Great potential in the use of *MusEcology* was seen within instrument making schools, especially for young instrument makers who still need to build their wood stock - this would also imply knowledge dissemination and awareness building on that topic. But this also applies to established instrument makers, who can influence the public and their customers through their awareness. The same is true for musicians and music students, who often desire traditional materials despite moral or environmental concerns because of their training and the assumed or existing expectations of their environment. Educating instrument makers, musicians and students is crucial, as they can drive change in each other and the broader industry.

6.2.1 Questionnaires

To evaluate and further improve *MusEcology* we set up an informal questionnaire study with 22 participating experts. The two videos of the supplemental material were shared as tutorial videos as an introduction to the tool and its functionalities. Next to basic questions (B1-B4) such as age, gender, background/profession, and level of expertise in additional domains, the questionnaires included five preference score questions (S1-S5) based on a 7-point Likert scale (ranging from *strongly disagree* (1) to *strongly agree* (7)) and three open questions (Q1-Q3). The test duration by the participants was, on average, 40 min. As guidance to explore the tool, we offered three scenarios, designed as different entrances and with the underlying domain-specific tasks (**T1-T8**) in mind (see Table 1). The participants came from the following domain backgrounds (B1): biology (8), instrument making (7),

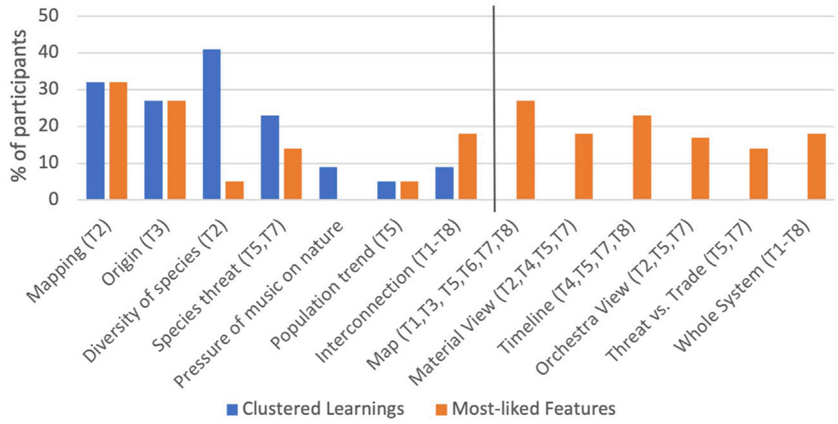

FIGURE 10
Clustered overview of learnings thanks to using *MusEcology* by questionnaire participants in blue on the left side. On the right side, explicit mentions highlight the clustered and most-liked features in orange.

musicology (4), and ecology (3), whereby some participants stated strong additional knowledge (B2) in wood sciences, geography and the other already mentioned domains. 41% of the participants assigned themselves to female and 59% to male gender, whereby no one made use of the given further options (B3). 73% of the participants were between 20 and 39, 18% older than 60 years, and 9% between 40 and 59 years old (B4).

6.2.2 Usability and support for decision-making

The survey inquired quantitatively and qualitatively about the usability of *MusEcology*. 86.4% stated they learned something new (S1 rating of $\geq$ 4). The open question allowed us to identify the learnings (Q1) of the participants (% of participants that mentioned this learning), which can be categorized into seven aspects that form part of our tasks and confirm their successful completion, aligned by the twelve most liked features (Q2, see Figure 10). Additionally to their new learnings, 95.5% of the participants rated that the visualizations helped to understand the complexity of the underlying problem (S2) with a score $\geq$ 5.Regarding possible improvements (Q3), three domain-specific desires were mentioned: Biologists in both evaluation steps pointed out that visualizing genuine/non-genuine changes in the timeline and considering multi-appendix and population listings in CITES would avoid misinterpretations. Wood science experts and enthusiasts desired access to macroscopic images, especially of the wood species. Musical instrument makers and musicologists needed to include common names for species and more explanations when hovering over acronyms, symbols, and icons. They desired additional mapping of further musical instruments and sustainable material proposals. In general, photographs or drawings of the plants and animals were mentioned to improve accessibility and support a better understanding, even for non-domain experts.

An important feedback from the participants was that 72.7% agreed or strongly agreed ($\geq$ 5) that *MusEcology* supports decision-making processes towards more sustainable musical instruments and species conservation (S3). Although 31.81% wished for better performance on their devices (5 of them reported interface issues), the system was evaluated as intuitive ($\geq$ 4) by 85.7%. Overall, *MusEcology* fulfills the intention to unveil a perspective for sustainability in musical instrument making, simultaneously serving for awareness building and enriching different research fields.

High-level decision-makers, such as those in CITES, can use this tool to quickly assess the impact of listing or up-listings of species on the music world. This enables them to provide for appropriate annotations in listing proposals that allow the listings to unfold the desired conservation effects, taking in account enforceability and implementation in practice. Often, decision-makers are unaware of the link between threatened species and musical instruments. Conversely, cultural traditions and their threats, like those discussed by UNESCO, can be better understood when the connection between instruments and endangered species is clear. This tool provides a comprehensive overview of 82 instruments and their constituent parts and the species from which these are made. Thereby, opening the perspective for these interconnections and facilitating the integration of cultural preservation into biodiversity strategies, which in turn may benefit species-specific conservation efforts.

6.3 Limitations and future work

Some limitations exist in data availability, such that we only had access to 388 distribution maps of 758 species used for musical instruments. Similarly, the selection of photos of the individual materials thus far is still limited to 209 of the different species. Another major limitation is data inaccuracy of information assigning instrument parts to specific materials. The designation in craft and trade is mainly based only on common names; therefore, possibly fewer species than presented here will be used in musical instrument making. This is especially the case for the species of the genera *Diospyros* (ebony) and *Dalbergia* (palisander/rosewood). The lack of distinctiveness of the wood of many ebony and rosewood species that could have been used for musical instruments, especially in the case of ebony, are part of the reason why many photographs of these species are missing and are not available on species level. The use of photos of the species *in situ* via e.g., photographs from Wikipedia or the IUCN Red List could enhance a more holistic perspective of the user that would lead to a perception beyond the material itself. Therefore we plan to implement a further interface switch to differentiate between the Material and Species View to make this point more clear and separated. That shall open the mind for the living organisms behind the materials and allows to switch between an anthropocentric and a more nature-centered perspective.

As already mentioned in the evaluation of the platform, possible misleading interpretations of data also represent a limitation. For example, the threat listings in the timeline do not indicate whether a change in the listing category was genuine or non-genuine. Thus, a change in the threat category does not necessarily imply a trend. Threat causes are another piece of information that users might speculate on, though not indicated in the platform. As part of a user-friendly design for casual users, we plan to include summed-up information per instrument as "cards", allowing them to quickly grasp the most important findings by small multiples. Such cards provide space to list the close-reading details, including relevant literature about these instruments with the indication of the used species per instrument. The amount of information originating from various sources and domains as well as the nested structures still require a certain understanding of the topics and use of interactive, zoomable visualizations and addresses therefore mainly experts. But with this *MusEcology* provides the foundation to use data and visualizations in further contexts and to create visual stories to communicate the underlying sustainability issues to a non-expert audience in an intuitive and memorable way. We have already used *MusEcology* as underlying system of an interactive visualization-based storytelling tool to reveal and disseminate the intangible cultural interlinkages and to introduce the visualizations and topics incrementally by multimedia annotations and expert insights (Kusnick et al., 2023), with more stories to follow in the future. Remarkable future developments would be the extension of ecological contextualization by including aspects of species threat at the level of ecosystems, e.g., occurrences of species in biodiversity hotspots. Projections regarding the potential effects of climate change, forest losses, and land-use changes in different ecoregions would enable the expert to give rough interpretations of future pressures on species used for musical instruments. So far *MusEcology* is assisting with research questions and raising awareness but is not giving concrete answers on pathways towards more sustainability such as the search for alternative materials. Including physical and acoustical material characteristics as well as further needed research findings on potential alternatives like discussed in (Yamada, 2017; Ryan, 2015a; Ryan, 2015b), would allow to develop visual guidance in the search for similar materials. In sum, this would enable a more comprehensive consideration of long-term aspects relevant to the sustainability of musical instrument making.

So far, our focus on musical instruments of the world is limited to classical musical instruments visually clustered in a symphony orchestra as a symbol for classical music. However, we intend to extend our approach that links musical instruments with the materials these are made of to other music cultures. Examples in literature for those relations are traditional pan flutes found in the Andes of Bolivia analyzed by Hachmeyer (2022), the traditional musical instruments located in the Brazilian Pantanal - the viola de cocho, ganzá, mocho and tamboril - as focused on by Kölble (2023), the termite-hollowed Eucalyptus trees in Australia for didgeridoos (Ryan, 2015a), as well as *shamisen*–a traditional Japanese instrument–threatened due to the dwindling availability of dog and cat skins used in its construction (Yamada, 2017). A database approach mainly focused on non-classical musical instruments and materials was chosen by Brémaud et al. (2007), although it did not link the materials to the ecosystems they originate from. Additional perspectives to these interconnecting subjects could be given by ecomusicologists complementing the already received musicological feedback from the evaluation. We believe in the future potential of disciplinary diversification of our connections and team to gain more scientific and practical domain expert insights and discover further data sets and possibilities. This design study contributes by opening a novel perspective on thematic approaches that would highly profit if picked up for future visualizations. For cultural traditions and arts, the reveal of the origin of used materials could be transferred to different contexts, e.g., natural materials for theater scenes or color pigments for fine art. Potentials for visualizations again are the invisible aspects of supply chains, such as "virtual resource consumption", e.g., the water used to produce jeans. Including fossil resources would also open a completely different need, e.g., for plastics or metals, visualizations regarding the various alloys and linking them as all fossil resources to global raw material deposits. Such as Devine (2019) highlighted the hidden costs of resource extraction, manufacturing, and waste regarding vinyl records, that replaced the shellac records, and ultimately the digital streaming. Bates (2020), on the other hand, examines the environmental costs of resource extraction with a focus on the metals tin and tantalum for audio technology components. Accordingly, environmental destruction, pollution, and their effects on society open further creativity fields for visualization design. Another contribution is the transferability to develop new thematic and representative schematic visualizations. Effective and understandable visualization elements can be created by involving multidisciplinary perspectives, such as the hierarchically structured Orchestra or Material View, enhancing statistical evaluations by domain-specific icons or multi-media elements.

7 Conclusion

Interconnected "global orchestra ecosystems" are threatened by various social and natural challenges such as climate change, biodiversity loss, habitat loss and fragmentation and require sustainable future pathways originating from distinct domains. By bringing together domain experts from ecology, biology, geography, musicology, instrument making, and computer science, we developed *MusEcology* as a platform to support sustainable environmental decisions. We combined various aspects relevant to the sustainability of orchestras with the materials used for musical instruments throughout different zoom levels, from the meta-level via the macro-level to the micro-level regarding species richness, trade-related and ecological threat in time and space, and the hierarchical taxonomic differentiation related to the material appearance.

By incorporating these various levels, we present a comprehensive, multi-dimensional view of sustainability, focusing on preserving both the cultural practices of orchestra music and the natural ecosystems that provide the raw materials essential for musical instruments. The interdependencies between these subjects are not obvious to various affected or interested user groups, therefore it is important to raise the lacking awareness, especially of connections across continents and beyond economic interests. With this combination, to the best of our knowledge *MusEcology* is the first visualization platform of a complex global cultural-ecological system that links academic with traditional knowledge systems considering space and time. The four interactive, multi-level views with their domain-specific visual metaphors invite users to immerse in the details of the materials used for the musical instruments of a symphony orchestra. By revealing the connection between the threat of species to threatened ecosystems, the platform supports decision-makers (e.g., instrument makers, policymakers) in understanding hidden connections for finding materials from less threatened species originating from less threatened ecosystems as sustainable alternatives leading to long-term impacts of their decisions. Pursuing from these details, this platform does not provide specific solutions for more sustainable musical instruments and orchestras; moreover, it shows that an orchestra ecosystem might require a multifaceted solution pathway. Existing approaches, for example, regarding material diversification and alternative materials based on physical and acoustic characteristics, need to include essential aspects for sustainability in a holistic understanding. Instead, such approaches need to consider the shown interrelations and consequences from perspectives of different domains to satisfy the complex requirements. During the development of *MusEcology* we discovered knowledge gaps in different fields. Ecological sustainability could benefit from more accuracy and data completeness of species distribution, population trends, and threats. Material science and instrument making should research alternative materials and investigate how they behave acoustically and physically in musical instruments. Cultural-ecological sustainability could consider approaches such as sustainable harvest, socially fair trade - documented transparently along the entire supply chain - or solution approaches that might affect or contribute to the loss of cultural traditional knowledge (e.g., new non-natural/artificial materials or modified materials). To identify protection priorities from an orchestra ecosystem's perspective, biodiversity hotspots offer a starting point for further interdisciplinary research to direct conservation activities to preserve the ecosystems an orchestra depends on. We plan to further enhance this platform of a global cultural-ecological system of a symphony orchestra in the manner described above as a base for more sustainability of musical instruments to raise awareness of and contribute to a balanced and harmonious interplay of nature and culture.

Data availability statement

The source code of the presented software is freely available. The web-application will be publicly available online in the near future. Most of the used data is freely available, whereby only the photographs won't be available for download, because of limited copyrights. Software Developer: Jakob Kusnick Contact address: kusnick@imada.sdu.dk Year first offical release: 2023. Software requirement: Google Chrome, Mozilla Firefox Program language: JavaScript Availibility: https://github.com/Vokabelsalat/musecology License: CC BY-NC-SA 4.0 Documentation: README in GitHub repository. Data Form of repository: CSV files in Zenodo. Author: Silke Lichtenberg Contact address: silke.lichtenberg@th-koeln.de Availibility: https://zenodo.org/records/10546544 License: CC BY-NC-SA 4.0 Documentation: README in Zenodo archive.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

JK: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. SL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing–original draft, Writing–review and editing. DW: Investigation, Supervision, Writing–original draft, Writing–review and editing. EH-S: Supervision, Validation, Writing–original draft, Writing–review and editing. UN: Supervision, Validation, Writing–original draft, Writing–review and editing. SJ: Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported in part by a grant from the Heinrich-Böll-Stiftung.

Acknowledgments

We wish to thank Prof. Gerald Koch and Dr. Volker Haag of the Thünen-Institut Hamburg for providing photographs of the extraordinary Mautz-Collections. We would also like to thank Emily Beech and Dr. Malin Rivers from Botanic Gardens Conservation International (BGCI) for sharing their expertise and their ongoing assistance regarding tree assessment data and representation of it. We sincerely thank the reviewers for their time and effort in reviewing our manuscript. We greatly appreciate their valuable comments, suggestions and ideas for future work, which have significantly contributed to improving the quality of our work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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