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Commentary

Historical exposomics: a manifesto

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Abstract

The exposome complements information captured in the genome by covering all external influences and internal (biological) responses of a human being from conception onwards. Such a paradigm goes beyond a single scientific discipline and instead requires a truly interdisciplinary approach. The concept of "historical exposomics" could help bridge the gap between "nature" and "nurture" using both natural and social archives to capture the influence of humans on earth (the Anthropocene) in an interdisciplinary manner. The LuxTIME project served as a test bed for an interdisciplinary exploration of the historical exposome, focusing on the Belval area located in the Minett region in southern Luxembourg. This area evolved from a source of mineral water to steel production through to the current campus for research and development. This article explores the various possibilities of natural and social archives that were considered in creating the historical exposome of Belval and reflects upon possibilities and limitations of the current approaches in assessing the exposome using purely a natural science approach. Issues surrounding significance, visualization, and availability of material suitable to form natural archives are discussed in a critical manner. The "Minett Stories" are presented as a way of creating new historical narratives to support exposome research. New research perspectives on the history of the Anthropocene were opened by investigating the causal relationships between factual evidence and narrative evidence stemming from historical sources. The concept of historical exposome presented here may thus offer a useful conceptual framework for studying the Anthropocene in a truly interdisciplinary fashion.

Keywords: exposome; environmental history; historical exposomics; digital history; social archives; natural archives

Introduction

The *nature versus nurture* debate is one of the oldest philosophical debates, dating back to ancient times (eg, Plato's Protagoras).[1] *Nature* is the genetic and biological "predetermination" of a human being, whereas *nurture* comprises all external factors influencing the individual from conception onwards. Today, this debate is—it seems—once more reframed as a scientific controversy opposing *genomics* to the concept of *exposomics*. With the highly funded Human Genome Project, next generation sequencing methods and genome-wide association studies (GWAS), genomics is both more mature and better financed than exposomics. However, interest in exposomics is increasing as many diseases cannot be traced back to genetics alone, but rather to the interplay of genetics and many other factors, which are captured under the exposome concept. The exposome covers all external influences and internal (biological) responses of a human being from conception onwards.[2] This paradigm[2] cannot be covered by just one scientific discipline; it requires a truly interdisciplinary approach. The "Luxemburg Time Machine" (LuxTIME) project is such an interdisciplinary setting—a "trading-zone" between different disciplines to find a common language between humanities and natural sciences. For this we propose the concept of "historical exposomics", aiming at interrogating the "trading zone"[3] between the exposome, history and data science to capture human influence on the natural world.

It is rare to find publications written from the perspective of both humanities and natural sciences due to the disciplinary specialization of each field. In general, both genome and exposome research is dominated by the natural sciences so far. Yet involving humanities in this research area, and more specifically adding a historical view, offers interesting perspectives for the exposome. Historical sources can help reconstruct the human exposome by revealing a multitude of historical data typically unexplored by the natural sciences. Exposomics evidence from the past is difficult to find in "natural archives" (the focus of natural sciences) present today. However, looking at "social archives"

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opens new possibilities to detect historical evidence (see Evidence section with an explanation of natural and social archives). By combining "hard" and "soft" facts, a more complex understanding of past processes of environmental change is possible. This article explores this based on the example of the interdisciplinary LuxTIME project from the University of Luxembourg.[4]

The LuxTIME project as an interdisciplinary framework

The LuxTIME project aims at exploring new ways of analyzing and interpreting factual evidence of the past by building an interdisciplinary framework for the investigation of "big data" of the past. Building on the conceptual premises of the "European Time Machine" Flagship project,[5] that is to bring together High Performance Computing (HPC) facilities, the analytical capacities of Machine Learning and Artificial Intelligence, and "big" and complex historical data, LuxTIME includes information from three different fields and scientific perspectives, namely eco-hydrology, environmental chemistry and industrial history. LuxTIME uses a local case (the industrialization of Belval in the Minett region of Southern Luxembourg)[6] as a testbed for methodological and epistemological reflections on how to study the long term impact of environmental changes on the health of the local population. By mixing "contextual information" based on archival evidence with "scientific evidence" derived from chemical, biological, or medical investigations, the project explores new grounds for interpreting big data of the past in a truly interdisciplinary setting.

Environmental history and the anthropocene

LuxTIME is inspired by the rapidly growing field of environmental history, which aims at analyzing and describing the co-evolution of human society and the natural environment.[7] The interdependence of humans and other living and non-living systems on Earth is recognized, and the unfolding of history is studied in the framework of the natural world. Recently, the human influence on the development of the ecosystem is being discussed and debated under the label of the "Anthropocene"[8]—a new temporal regime and ecological period marked by the human imprint on the natural world, including the "Critical Zone", the Earth's skin which sustains nearly all terrestrial life including humanity.[9-12,13]

For most of the time since the origins of humankind, the population was too small, spatially scattered and technologically undeveloped to markedly influence the environment. With the Neolithic Revolution (~10 000 BCE) and the change from a hunting and gathering lifestyle to one of agriculture and settlement, the human species learnt new ways to modify the environment to serve their purposes. Deforestation, irrigation,14 the development of systematic sowing methods and the use of fertilizers drastically increased food production, allowing for a surge in the human population size. In 10100 BCE the population rose above 5 million. With this came the development of trading networks and complex societies.[15] Ecosystems were brought out of their natural balance.[16] Soil erosion and salinization, the depletion of nutrients or a rise in infectious diseases were some of many consequences accompanying these technological advancements.[17,18] From the Roman Era to the Middle Age, new technological development of iron metallogeny and intense mining activities also enriched in heavy metals the local atmospheric deposition all over Europe.[19,20]

Since then, the scientific (~1540s) and industrial revolution (~1780s) have resulted in countless inventions, which have left their environmental traces on Earth. This process, ideologically framed as era of "modernization" and narrated as a history of "progress", has left a long-lasting toll on the planet.[21] It is estimated that humans have transformed 20 to 100% of all land surfaces.[22,23] The release of pesticides, fertilizers and other chemical contaminants is interfering with natural ecosystems, resulting in large-scale biodiversity loss and deterioration of soil and water quality.[24] Recent extinction rates are estimated to be 100 to 1000 times higher than the average rate on geological time scales.[25] Chlorofluorocarbons (CFCs) have spread to the upper layer of the atmosphere and depleted the ozone layer, which protects the Earth from ultraviolet radiation coming from the sun.[26] Microplastics have been detected in various environments, including the air, oceans and freshwater eco-systems.[27] The aftermath of anthropogenic activities affecting the natural environment is expected to persist for long time periods (>50 000 years).

The various developments arising from the wasteful and harmful treatment of the environment by the human species stimulated the rise of preservationist and conservationist philosophies[28,29] in the late 19th and early 20th century, acknowledging the boundaries of nature and advocating a wise and efficient use of resources where humans should see themselves as an integrative part of the natural environment, rather than the conquerors thereof. This has evolved to the global environmental movement of today, which includes a wide range of activist organizations, political parties, scientific organizations, and governmental policies focused on promoting environmental values, and combatting detrimental behavior, such as the emission of greenhouse gases, deforestation and pollution.[30]

The United Nations assumed a key role in debating climate change and global environmental issues in the political sphere. The 1972 United Nations Conference on the Environment in Stockholm was the first international conference connecting economic growth and human well-being to environmental aspects such as the pollution of air, water and the oceans.[31] The 1992 United Nations Conference on Environment and Development (UNCEP), held in Rio de Janeiro, composed a declaration of 27 principles aimed at guiding countries to a sustainable future, where "human beings are entitled to live healthy and productive lives in harmony with nature".[32] The Montreal Protocol of 1987 aimed at phasing out ozone depleting substances such as CFCs.[33] It is, to date, the only environmental treaty ratified by all 198 UN member states and is regarded as a benchmark in multilateral environmental regulation. The Kyoto Protocol of 1997 and the Paris Agreement of 2015 aim at reducing greenhouse gas emissions and limiting global warming to 2°C compared to pre-industrial levels.[34,35] In 2001 the Stockholm Convention on persistent organic pollutants (POPs) was signed, a global treaty to minimize the risk posed by POPs to the environment.[36] The initial list of 12 ("the dirty dozen") compounds prepared by the intergovernmental negotiating committee (INC) is extended regularly and to date covers 23 unique compounds (including the commercial mixture of decabromodiphenyl ether, c-decaBDE) and 8 compound classes (including compounds that are listed with their salts, isomers or esters) to be eliminated or restricted.

History and the exposome: a conceptual discussion

Critique of current approach

In his famous 2005 paper, the epidemiologist Christopher Wild was one of the first to give the complementary concept to the genome a name: the exposome. According to Wild, the exposome includes "life-course environmental exposures (including lifestyle factors) from the prenatal period onwards".[37] Gary Miller and Dean Jones extended the concept of the exposome in 2014, shifting the focus of the exposome beyond solely the exposures.[38] They expanded the concept adding the aspects of diet, behavior and endogenous processes, with a particular focus on the biological responses to exposures. Even genetic and genomic alterations serve as evidence of past exposures.[39] The resulting shift in exposomics research from exposure-focused (introduced by Wild)[37] to more metabolomics focused approaches[38] to capture biological endpoints has been accompanied by several changes. Of course, the study of internal metabolic changes and the search for biomarkers in exposomics research is highly necessary, but not the sole goal of exposomics. The last years showed a trend to using increasingly expensive resources and sophisticated techniques, rather than focusing on the initial research question. Research is driven by metabolomics approaches using databases that contain mostly "known" knowledge, necessary to ensure workflow efficiency, yet at the same time trying to find new discoveries and improve the understanding of metabolic pathways. However, with the rapid pace of innovations in the age of the Anthropocene, new synthetic compounds (and their related transformation products) are appearing at an alarming rate with up to 20 million new registrations a year,[40] which can cause new problems and influence the human metabolism very differently. Although it is possible to create dynamic workflows and databases to profit from "new" knowledge generated via high throughput exposomics (eg, PubChemLite for Exposomics[41]), this requires concerted efforts at FAIR and Open data exchange,[42,43] for which resources and infrastructure are still under development. The exchange of information will be vital to support reinterpretation of older data (eg, retrospective screening[44,45]) or large community initiatives for large scale discovery such as the Global Natural Products Social Molecular Networking (GNPS) ecosystem.[46] However, while modern analytics and monitoring techniques can help capture relatively recent perturbations in the exposome, even using natural archives to an extent to investigate past pollution, there is a limit to the availability of suitable samples. The historical exposome concept can give additional perspectives to this technologically driven bio-exposome. Looking at environmental history as such, especially focusing on developments in the Anthropocene, can show many interconnections of environment and health, where expensive technological studies using biological samples of today may fail to find these connections. Historical archives can, for instance, reveal if currently perceived extreme events such as drought or flooding (relative to written records of ∼100 years) were in fact observed centuries earlier. Closer to the exposome, anecdotal, written documents (letters, newspaper articles) can also reveal the catastrophic side-effects of industrial pollution in factories, which is only partially captured in scientific literature (and if covered, often in foreign languages).[47]

Definitions of the environment

One way to approach the exposome from a more holistic perspective is to embed it into the wider framework of what has been called "the environment" since the early post-war years. As demonstrated by the three environmental historians Paul Warde, Libby Robbin, and Sverker Sörlin in their book "The Environment. A History of an Idea",[30] the term gained prominence as a political concept as a result of the success of popular science writers such as William Vogt ("Road to Survival", 1948)[48] and Rachel Carlson's best-seller "Silent Spring" (1962).[29] Although the term had been around for more than a century ("milieu" in French, "Umwelt" in German), a transformation of meaning from "a world where man was molded by environment to him being able to alter the nature of his world"[30 (p. 8)] only occurred with the "environmental revolution" in the 1970s.[49] Sparked by new academic interventions such as the "Limits to Growth" report to the Club of Rome in 1972[50] and the first "oil crisis" in 1973, ecological thinking became a mainstream concern for both scientists, environmental or ecological movements, and world politics. The problem of "the environment" became both scaled (ie, local problems of pollution or waste were interpreted as a subset of a planetary issue) and the result of a complex interplay of past, present, and future temporalities.[21]

To handle the growing complexity of issues at stake, new concepts such as the "ecosystem" were put forward to highlight the holistic nature of environmental changes. Inspired by the post-war boom of "systems theory" and "cybernetics", and long before climate science would emerge as a new interdisciplinary field, even Eugene and Howard Odum introduced the metaphor of balance between the living (organic) and nonliving (abiotic) environment in their textbook "Fundamentals of Ecology" (1953).[51] Ecosystem science became an important framework for setting up large-scale international research projects, shaping the thinking of the environment as a dynamic interplay between "nature" and "nurture" in a system called "earth" at a planetary scale.[30 (pp. 154–158)] Since the introduction of the concept of the "Anthropocene" by Paul Crutzen and Eugene Stoermer in 2000,[8] the human factor has entered the equation: according to recent scholarship, both the living and the nonliving environment has been radically affected by human activity on earth, crossing planetary boundaries.[52-54] With the human being acknowledged as an ecological factor in history (as had been suggested by historian long before),[55] the concept of environment as a tripartite dynamic system has emerged, combining the "natural" environment with the "human built" or socio-technical environment and the subjective environment of the individual.

This "holy trinity" of natural, individual, and social factors that form "the environment" suggests that the physical surrounding in which life takes place, which is comprised of the atmosphere, the biosphere, the hydrosphere and the lithosphere,[56 (p. 14)] is fundamentally interconnected with human activities on earth. We cannot grasp the full complexity of one element without considering the impact of the others. The interconnected, dynamic relationships render "the environment" an incredibly complex system that seems hard to grasp—even from a truly interdisciplinary perspective. Yet it is this "maelstrom" of temporalities, scales, and uncertain causalities that challenges mono-disciplinary approaches and interdict mono-causal scientific explanations.[55] What is needed are new questions, concepts, and narratives aiming at forging an understanding of past and present environmental challenges, starting with a new search for evidence in and significance of existing data from both natural and social archives. Combining evidence from historical and natural sciences and thereby bridging the "two scientific cultures" is a key condition for performing historical exposomics research.

Finding significance in a different way

The search for significance is a common factor across all disciplines. Experts from the fields of humanities, natural and social sciences aim to make significant contributions in their areas of research. In a more general sense, significant contributions have the quality of being important, of being worthy of attention because they answer relevant questions and have meaningful results. In practice, the mindset, practices, and evaluation methods of assessing significance are often specific to each discipline, with a diverse range of views also present within each discipline.

One reason may be the nature of the information sources in each discipline. Focusing on the fields of history and natural sciences, a historian works more frequently with primary sources such as historical manuscripts or photographs, while a researcher in natural sciences often works with numerical data resulting from measurements. The inherent difference in the nature of the sources, as well as the *a priori* impossibility of making measurements in the past or repeating an experiment, lead to different approaches to the assessment of significance. Additionally, an apparent widespread dualism can be perceived, where natural sciences more often try to prove a theory that can be generalized for a larger population, whereas history is more frequently concerned with specific knowledge about a particular fact or occasion, with the consequent differences in the researcher's approach to significance.

Statistical hypothesis testing is an inference method widely used in natural and social sciences to determine a possible conclusion between two hypotheses. A null hypothesis is defined against an alternative hypothesis and the *P*-value is defined as the probability, calculated under the null hypothesis, that a test statistic is as extreme or more than its observed value. If the *P*-value is less than the selected significance level, then the null hypothesis is rejected. Traditionally, a $P\text{-value} < 0.05$ has been considered a reasonable significance level, but in some fields such as genomic studies, more stringent levels are adopted. The criticism of this method is extensive across fields of research,[57-60] including technical limitations such as the difference between the characteristics of the scientific data as opposed to the assumptions upon which the significance tests are defined, sampling issues regarding size and randomness, the arbitrary level of significance, the dichotomous reject/not-reject, the misinterpretation of *P*-values and the lack of reproducibility. However not only technical issues have been raised, but the actual scientific value of the tests has repeatedly been questioned, pointing out weaknesses in the use of isolated tests, the difficulty to generalize results and to integrate previous knowledge, causing erroneous scientific reasoning.

Numerous options have been proposed over decades of research, from the use of stricter *P*-values to the total abandonment of statistical significance, as well as a wide range of alternatives,[61-63] but the statistical significance in hypothesis testing is still a widely used method due to its intuitive interpretation, ease of calculation with existing tools, and facility given to the choice of the research path with yes/no questions. Bayesian approaches, older than frequentist statistics, gained popularity with the advances in computational methods. Bayesian methods depend on a prior and on the probability of the observed data, allowing the sensitivity of the experiment result to be measured for different priors.[64,65] In Bayesian inference, the uncertainty or "degree of belief" with respect to the parameters is quantified by probability distributions.

Controversy about statistics at a more general level includes the opposition of two attitudes to the question of reality, one realistic or objectivist (ie, pre-existing); and the other, relativistic or historicist (ie, constructed),[66] very present when bringing together history and natural sciences. In *Trust in Numbers*, Theodore M. Porter challenges the ubiquity of quantification in the sciences of nature, highlighting that only a small proportion of the numbers and quantitative expressions "make any pretense of embodying laws of nature, or event providing complete and accurate descriptions of the external world".[67]

There is an increasing interest in qualitative research methods across disciplines, such as research techniques that rely on non-statistical or numerical methods of data collection, analysis and evidence production. Qualitative research allows to retain complexity and nuance through data collection methods that adapt to the context and make it possible to explore emergent issues; and they present a reflexive approach that acknowledges the perspective of the researcher in the process.[68] They are used in the social sciences and the humanities, but they can also complement quantitative approaches in the natural sciences.[69] Qualitative research can be used independently to uncover topics that are not amenable to quantitative research. Furthermore, it can be used as the preliminary of quantitative research, that is to uncover ambiguities and misunderstandings regarding terms and definitions, to help understanding the reasons behind certain results, or to validate quantitative research by providing a different perspective on the same phenomena, sometimes forcing major reinterpretations of quantitative data.[70] Despite the many potential applications, qualitative methods are often evaluated according to quantitative measures of rigor and dismissed as unscientific and unreliable.[71]

Criteria of significance in history includes two main questions: what is important to learn about the past and how do historians know what they know. The first refers to deciding which events or people resulted in a change that had deep consequences. The second is about the historical interpretation based on inference made from sources: what questions turn a source into evidence, who created it, when and for what purpose, what is the historical context and w the inferences can be corroborated.[72] Partington[73] identifies three criteria of significance. First, the importance to people in the past "if we use the egalitarian principle of counting heads to establish priorities here we are in difficulty, because we have unequal access to the opinions and judgements of different social and ethnic groups [...]."[73] Second, objective criteria that includes profundity, as whether an event profoundly changed people's lives; quantity, as the number of lives impacted; and durability of the event in time. Thirdly, criterion is relevance, or how an event contributes to an increased understanding of the present.

An interdisciplinary approach to historical exposomics blurs the boundaries between discipline-specific approaches to significance and makes it possible to study the past from new perspectives. Historical sources like pollution measurements included in official reports, complaint letters from the citizens about the dust from the factories and contaminated water, newspapers publishing about new labor laws, innovative industrial techniques, or disease outbreaks, can be used to test hypotheses about pollution concentration or the impact on health in the past, while assessing at the same time for historical significance. The historical archives are filled with scientific and non-scientific, numerical, and non-numerical sources, that together with current scientific knowledge and measurements about water systems or use of chemicals, allow to simulate and validate hypothesis about the past. The dualism "specific" versus "universal" between science and history is replaced by a combination of close and distant reading from a historical and scientific point of view adapted to the source and specific analysis, which allows access to much more information, to analyze it from different points of view, and to use multiple approaches to assess significance.

Evidence from social and natural archives

A historical exposomics approach requires the combination of a great variety of historical and current data. As shown here using data collected for the research project "LuxTIME" as an example, the information gathered comes from both "natural" and "social" archives. Natural archives are physical objects which have been collected, processed and deposited in the environment under natural circumstances (ie, without the interference of the human species), and preserve information about the characteristics of the surroundings from the time and place where deposition took place.[74] Through various analysis techniques, this stored information can be extracted from the archive, enabling the reconstruction of environmental conditions far beyond the period where direct measurements have taken place. This helps determine the baseline conditions at the time, as well as spatial and temporal changes, allowing researchers to relate these to natural or anthropogenic influences.[75]

Social archives

Social archives refer to archives that are the result of a conscious and directed collection of past evidence, be it for cultural (religious, artistic), political (administrative, governmental, legislative), or economic (companies, trade) purposes. Information stored in such archives (be it textual, audio-visual, or material remains/objects) provide documentary evidence of past activities that have shaped the environment, be it through new production and consumption processes, regulatory or legal procedures, or political and cultural discourses on scientific or technological progress, nature protection or market and trade regulation. Based on methods of historical source criticism, social archival records are important to contextualize the development of science, technology, industry production, agriculture, energy consumption and all other human activities that have shaped our contemporary environment.[76] The information or data that can be extracted from social archives contains different kind of evidence, such as narrative data (eg, weather reports on newspapers), long series of quantitative proxies (eg, by procedures related to census or fiscal data), illustrative sources (photographs, drawings, maps), and instrumental measurements (eg, research diaries).[76] Such sources have been used extensively for the production of a rich historiography on Luxembourgish steel industry and the industrialization of the Minett region more generally.[77-79] Comparative studies on the emergence of coal and steel industries in various European regions have highlighted the specificities of the Luxembourgish development, both in terms of availability of natural resources and its dependencies on technology and capital transfers (especially from the Ruhr region), economic alliances (such as the adherence to the German "Zollverein" [customs union] until the end of the Great War), and political constellations (such as the creation of the European Community of Coal and Steel [ECCS] in 1951).[80-84]

The LuxTIME research efforts included consultation of many different archives in Luxembourg, including national and local archives, libraries, museums, and deposits of public administrations (see Figure 1).[85] The sources from these archives were categorized and indexed, specifying the temporal and spatial coverage as well as the exposome category that the sources are referring to (eg, physical/chemical; ecosystem; lifestyle, etc.). The analysis of this data inventory of the social archives has been turned into a treemap showing the number of datasets covering exposome categories and subcategories, see Figure 2.

By means of example (without any claim for comprehensiveness), the following sections describe several natural archives that have been studied or were considered in the framework of the LuxTIME project.

Historical groundwater reserves

Groundwater serves as an archive for historical climatic and hydrological conditions. When aquifer recharge takes place, the ambient environmental conditions are stored in the precipitated water as chemical and isotopic signals, which preserve sequential changes as the groundwater moves away from the point of recharge.[86] Extracted groundwater samples, once related to a proper chronology, for example through radiocarbon dating (^{14}C), have been found to provide indications about the temperature, air-mass circulation and rainfall intensity of the past.[87-89] In its simplest sense, the mere presence of dated groundwater can be an indicator for prolonged wet periods, while absence thereof is a sign of no recharge, possibly due to a period of drought or ice cover.[86,90] The concentration of dissolved noble gases in groundwaters is a function of the temperature and salinity at the time of recharge (Henry's Law). The concentration decreases with increasing temperature.[91] Since these concentrations are largely unaffected in groundwater bodies, this relationship can be utilized to establish historical temperature records.[87,89,92] The stable isotopes of water (H and O) are separated into heavier and lighter compounds as they move through the hydrological cycle. This creates an isotopic ratio characteristic to the air temperature and humidity at the time of groundwater recharge, as well as environmental processes such as evaporation and condensation.[93] These isotopic ratios have been utilized to reconstruct air-mass circulation and temperatures of the past.[89,92] Age dating uncertainties and mixing of different waters in the aquifer over time creates a smoothing of the signal fluctuations. Groundwater thus serves as an archive which stores an average of the conditions at glacial/interglacial time scales.[89]

Freshwater bivalves

Stable isotopes of oxygen and hydrogen in precipitation and stream water are used for conceptualizing and modeling hydrological, ecological, biogeochemical, and atmospheric processes.[94-97] However, their full potential—for example in climate change impact studies[98] or climate and earth system modeling[99]—cannot be leveraged due to short and truncated time series.[100,101] A promising way forward for reconstructing the history of flowing waters is the conceptualization of rivers as living entities.[102,103] Past changes in eco-hydrological catchment functions and their impacts on freshwater habitats may eventually be recorded in natural archives (and *vice versa*). This feature qualifies trees and freshwater bivalves as (biotic) sensors for reconstructing chronologies of past climate and flowing waters into pre-instrumental times. During the growth process, bivalves (or mollusks) record environmental data in their shells in the form of variable geochemical and microstructural properties, as well as variable increment widths, like tree rings. Controlled by biological clocks, the shell growth process occurs periodically and eventually results in the formation of growth patterns (representing periods of fast and slow growth) that can then be placed in a precise temporal context. By archiving in-stream environmental

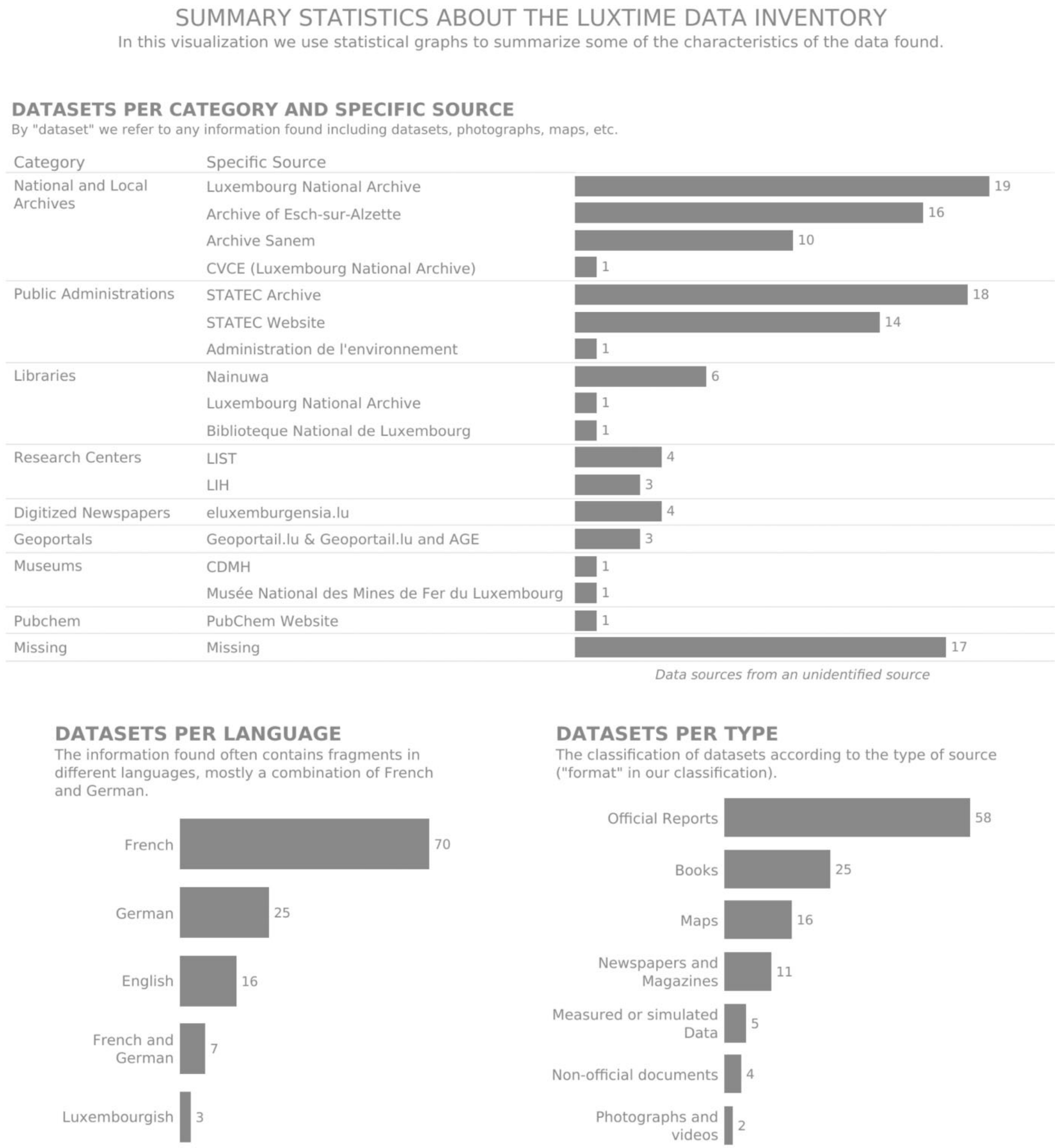

Figure 1. Summary Statistics Data Inventory for the LuxTIME project.

conditions,[104,105] freshwater bivalves thus show considerable potential for complementing stream water isotope records. By forming their shells near equilibrium with the oxygen isotope value of ambient water, changes in isotope values in the shell (represented as $\delta^{18}O$ values) can serve two different purposes. They may help in reconstructions of both stream water temperature (if water $\delta^{18}O$ values are known) and $\delta^{18}O$ values (provided water temperature during shell formation is known or can be reconstructed by other means). While stream water temperature reconstructions have been extensively used,[104] hydroclimate reconstructions have received considerably less attention.[105] Recent proof-of-concept work has demonstrated the potential for freshwater mollusks to solve the problem of limited $\delta^{18}O$ isotope records in stream water.[106,107] New analytical protocols based on Secondary Ion Mass Spectrometry have revealed the previously untapped variability in stream water $\delta^{18}O$ signatures over nearly 200 years and their connection with changes in atmospheric circulation patterns.

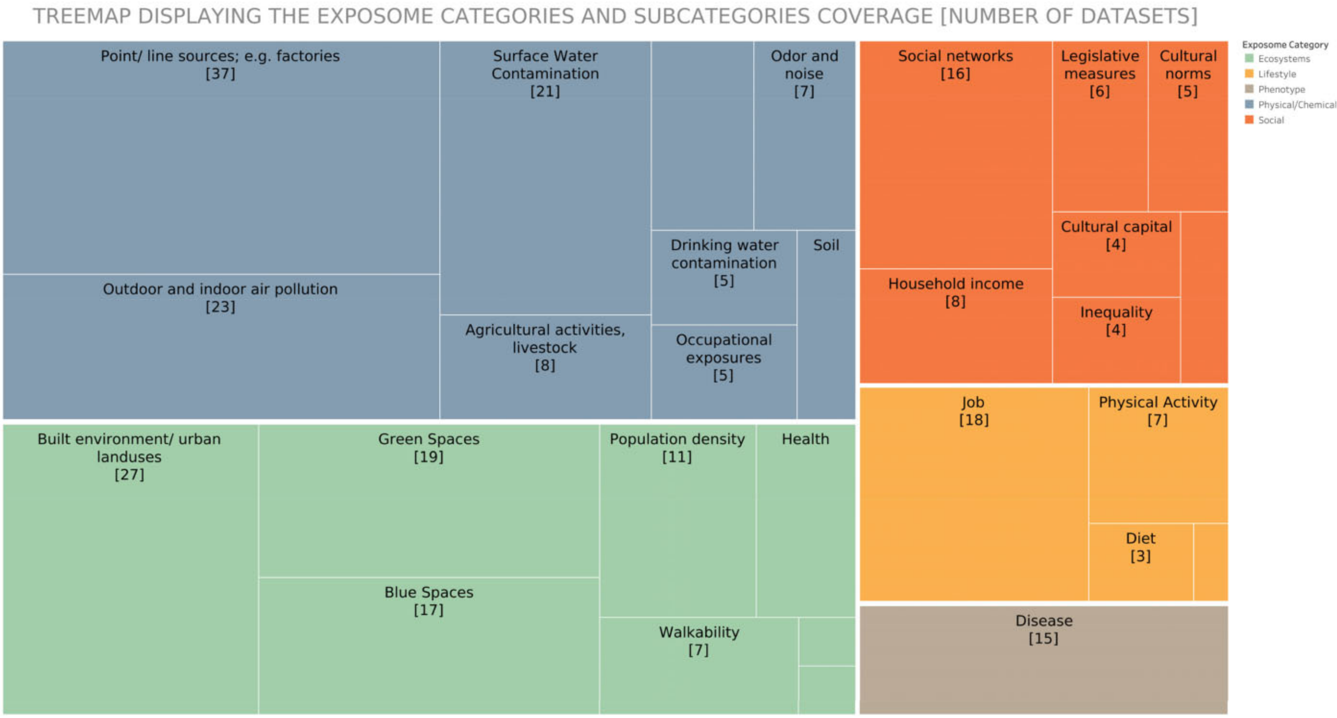

Figure 2. Treemap visualization of exposome categories and subcategories covered by the data inventory.

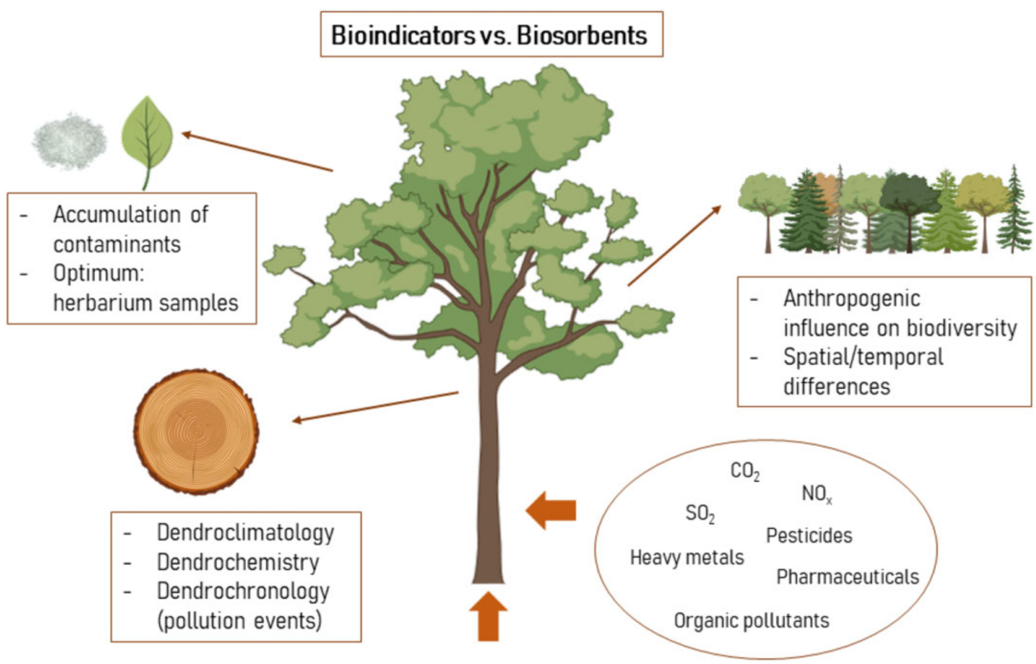

Figure 3. The function of trees as bioindicators versus biosorbents.

Botanical samples

Many studies show that botanical samples can serve as evidence for the impact of man in the age of the Anthropocene.[108-113] Plants, as sensitive organisms, respond strongly to anthropogenic influences such as air pollution. The susceptibility of plants to air pollution can be evaluated by their Air Pollution Tolerance Index (APTI), which is determined by the parameters ascorbic acid, chlorophyll, relative water content, and leaf-extract pH.[114] The APTI is often used studying the potential of plants as biosorbents (remediation activities)[115,116] or bioindicators (biomonitors)[113,117] of pollution (Figure 3).

Plants, such as trees, can be considered as evidence for historical events and thus as natural archives. Trees can provide accurate information about climatic conditions in the past,[118] using dendrochronology information (dendroclimatology). Additionally, those measurements can help to differentiate between natural and anthropogenic causes (increase of CO_2 and other gases) of changing environmental conditions.[119]

The population of specific species in certain areas is often connected to human activities. For example, tree species such as birch and alder grow well at post-mining sites, even in highly "contaminated" mine soils, and can even change the microbial properties of the soil.[120,121] As the biodiversity of an area depends directly on factors such as soil, air or water contamination, any changes in plant species may correspond directly or indirectly to an (anthropogenic) change in the direct ecosystem. Analyzing the age of those species could even provide information about the date of these environmental changes, for example, the time of reforestation in post-industrial areas. While looking at historical documents about the influence of air pollution on plants, geographical mapping of species can be found, even if no measurement data is available.[122] If one examines plant species for environmental contamination, one can—under favorable circumstances—make statements about the health of an ecosystem (even in the past). This can be done, for example by analyzing lichens,[123-125] which act as a chemical filter for air pollution, accumulating contaminants over many years. The same applies for tree bark and leaves,[126] however, the time point of pollution is not analyzed in most studies. In the optimal case, one can resort to archived plant samples from herbaria, for example, for the analysis of per- and polyfluoroalkyl substances (PFAS) in pine needles,[127] although samples need to be stored suitably to allow for this analysis. Moreover, using state of the art techniques like matrix-assisted laser desorption ionization—imaging mass spectrometry (MALDI-IMS) allows the monitoring and localization of the contaminant uptake and distribution pathways through the plant.[128,129] There are some studies using tree rings as archives of atmospheric pollution, which can be analyzed in a temporal and spatial manner (dendrochemistry).[108,112] However, there are several limitations and uncertainty factors, such as soil acidity or growth rate to be considered.[130,131] In general, looking at botanical samples always has some uncertainty factors due to plant metabolic processes altering concentrations, as well as external influences (eg, sample handling) influencing all research outcomes—but could nonetheless reveal interesting information about the past that may not otherwise be accessible.

Data visualization

Both natural sciences and humanities use data in their research, whether they are historical or modern texts, measurements from observations or experiments, elements of a photograph, time series, geographical data or many more. Data is the connecting element in interdisciplinary research. Various disciplines often share data analysis methods, but also share the same challenges, such as how to discover what is relevant for their specific research question when dealing with a large volume of data, how to validate the data, or how to communicate the results to readers according to their specific needs. They also face fundamental differences in the definition and use of data and the required communication objectives. Data visualization supports multiple scenarios including discovery and communication. It helps to navigate large volumes of data, whether to perform an initial exploratory data analysis to define the line of research, or to make discoveries that form part of the project results. It is also essential for communicating results, which allows creation of the desired user experience in each case.

Especially in the context of interdisciplinary projects, it is important to understand the different approaches to data visualization since a combination of these might be required for the analysis of data from the point of view of different disciplines. In the case of the natural sciences, data visualization is generally used as a tool to simplify a complex topic, to make data-driven decisions about the best path of research, to build upon previous scientific knowledge by integrating references and benchmarks, and to communicate a clear message to an audience. Scientific data visualization is largely based on statistical graphics which are characterized by the principles of abstraction, reduction, standardization, representation, and legibility. The user is expected to be familiar with the visual elements—the statistical charts, for example, bar charts, line charts—and to ask predefined questions to get formatted answers, to apply filters, and to drill down to predefined levels of aggregation. In the case of the humanities, the use of data visualization often aims at showing the complexity of the subject of research, to engage the user in the interpretation and to present multiple narratives. The data visualization is defined by its granularity, specificity, and full coverage.

To study historical exposomics, data visualization techniques such as concept maps can be used to understand the specific contributions of each field and the joint area of work, see Figure 4.[85]

During the exploration of the data, the use of data visualization allows identification of the types of data available—time series, geographical, texts, images—the geographical area and the period covered, the variety of sources—historical archives, sampling campaigns, web archives—the domains—air, water and soil pollution, demographics, health, industry, urbanism, green and blue areas—and the percentage of sources digitized, among others. This facilitates the identification of gaps, areas of interest and future challenges. Lastly, one of the most frequent use of data visualization is to share the research output. A combined approach to data visualization, scientific and humanistic, allows integration of representative analyses to understand the general impact of the main environmental exposures on health and exploration of the different narratives by integrating individual cases, when relevant.[85]

New historical narratives

In studying historical evidence of human traces on the environment by applying both scientific and hermeneutic methods of interpretation, LuxTIME aims at contributing to a new form of data-driven scholarship on the Anthropocene by experimenting with digital forms of historical storytelling, such as animations of dust pollution in Esch-sur-Alzette over nearly one century (1911–1996) shown in the website "minett-stories" and in Figure 5.

The animation that was produced within the virtual exhibition "Minett Stories"[132]—an interdisciplinary public history project in the framework of the "Esch22/Capital of Europe" initiative,[133] was the result of a collaboration between historians, metallurgy experts and chemists. Based on a data set including information about the production output of the Belval steel plant throughout the 20th century, the type of production process (eg, LD-AC or Thomas for steelmaking), the typical usage of filtering systems, and the prevailing wind directions in Luxembourg over time, the animation offers a plausible approximation of how the dust emissions of the Belval iron and steel complex might have affected local air quality over the decades. Even if the animated map can only offer a hypothetical approximation rather than an exact reproduction of past reality, such temporal visualizations can trigger our historical imagination and open new paths for further historical investigation.

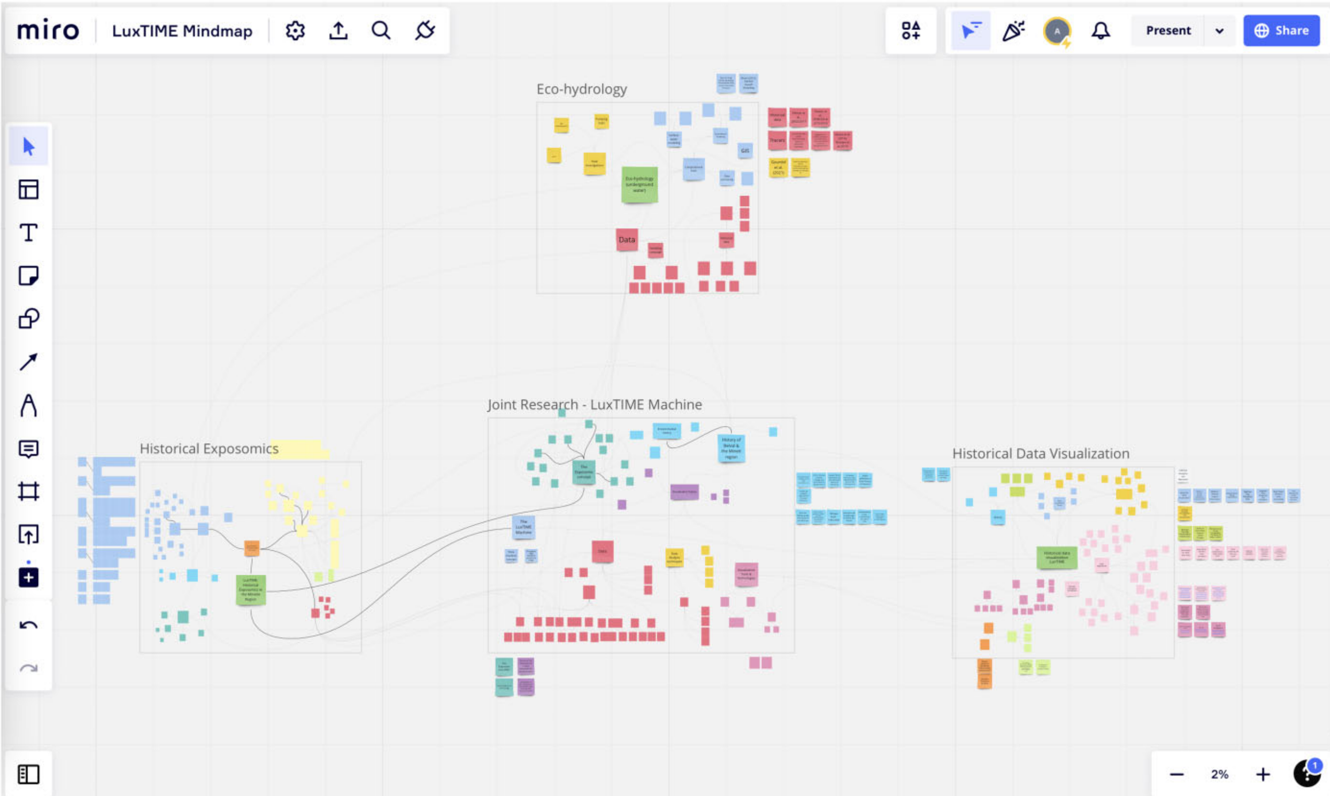

Figure 4. LuxTIME Concept Map including History, Data Visualization, Environmental Cheminformatics and Eco-hydrology.

Figure 5. Screenshots from the Minett Stories Website (https://minett-stories.lu/en/story/air-pollution-visualized).

Conclusions

Bridging the gap between "nature" and "nurture" by bringing a great variety of different historical sources and datasets together is an exciting and challenging exercise in interdisciplinary collaboration. While the LuxTIME project was conceived as a testbed for data-driven scholarship in the field of environmental history with a focus on the Minett region, the interdisciplinary collaboration in the team has opened new research questions and approaches beyond the field of environmental humanities. In exploring the concept of "historical exposomics", this article hopes to make a convincing argument for enlarging the scope of current research on the exposome by enriching it by historical evidence from "social archives". In contextualizing the data from both natural and social archives and investigating the causal relationships between factual evidence from the sciences and the narrative evidence stemming from historical sources, new research perspectives on the history of the Anthropocene can be opened, challenging classical forms and formats of historical storytelling and interpretation.[134] The concept of historical exposome, such is our hypothesis, might offer a useful conceptual framework for studying the Anthropocene in a truly interdisciplinary fashion.

Future efforts in this field require research and training in "digital hermeneutics", looking critically at the use of digital tools and (big) data of all kinds (as covered by the Digital History &

Hermeneutics Doctoral Training Unit DTU of the C^{2}DH).[135] Interdisciplinary collaboration is required for the testing of hypotheses and scientific interpretation of evidence studying the historical exposome. Finding a common language to discuss past, present and future exposomics-related developments is required to tackle this challenging topic.

The historical exposome is presented here as an interdisciplinary approach to address the exposome. Adding value from both perspectives, natural sciences and humanities to study this highly complex paradigm opens new possibilities for present and future research. Instead of solely performing expensive cohort studies looking at the present state, looking at past digital data already present can provide valuable insights. If scientists wish to learn from the past, they must dig into the past, as physical evidence often is not present to be analyzed today. Social archives provide a wealth of soft and hard data sources of information. It is worth investing time to look at historical documents, perform simulations to estimate the past state and even go one step further and simulate future developments. In terms of environmental pollution, looking at past evidence might often prove to be more useful to find for example connections to present day diseases, than analyzing present evidence (eg, looking at past exposure to pesticides studying present day Parkinson's disease[136]). Combining it with today's state of knowledge and tools can help to improve the understanding of the exposome and may help prevent further environmental contamination and disease.

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Author Contributions

Dagny Aurich (Conceptualization [equal], Data curation [equal], Visualization [equal], Writing—original draft [equal], Writing—review and editing [lead]), Aida Horaniet Ibanez (Conceptualization [equal], Data curation [equal], Visualization [equal], Writing—original draft [equal], Writing—review and editing [equal]), Christophe Hissler (Conceptualization [equal], Writing—original draft [supporting], Writing—review and editing [equal]), Simon Kreipl (Conceptualization [supporting], Writing—original draft [equal], Writing—review and editing [equal]), Laurent Pfister (Conceptualization [equal], Writing—original draft [equal], Writing—review and editing [equal]), Emma Schymanski (Conceptualization [equal], Funding acquisition [equal], Supervision [equal], Writing—original draft [supporting], Writing—review and editing [lead]), and Andreas Fickers (Conceptualization [equal], Funding acquisition [equal], Supervision [equal], Writing—original draft [equal], Writing—review and editing [equal])

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Conflict of interest statement

None declared.

Data availability

Not applicable.

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