Short Note

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Learning from the Multiple Fossil Records—Bridging a Gap Between Modern Research and Teaching Practices in Paleontology Education

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Abstract: Physical specimens have been always the primary resources for teaching and learning paleontology in formal educational environments. However, there is a growing interest in the use of paleontological data in higher education, supported by the increased use of digital tools and large paleontological databases for data-driven learning (DDL). In the context of the ongoing data revolution in modern paleontological research, the notion of the two fossil records has emerged to distinguish the physical record consisting of specimens, from the abstracted record consisting of the data derived from those specimens. Here we argue that the so-called abstracted record extends beyond the digital data (e.g., databases, digital models, and imagery) to include (*i*) network-based representations of high-dimensional fossil data (e.g., The Earth-Life System), and (*ii*) point process models describing spatially explicit events (e.g., community-scale spatial distributions; distribution of biotic traces on shelled invertebrates). We discuss these multiples fossil records from a didactical perspective, highlighting their promise for DDL in the paleontology classroom. Network science and spatial point processes modeling are transforming paleontological research by enhancing modeling capacities and helping researchers to reveal the complexity of the global biosphere over deep-time. Our perspective paper aims to bridge the gap between the state-of-the-art paleontological research and current teaching practices in higher education courses of paleontology, by calling on educators to leverage these breakthroughs into their classrooms.

Keywords: paleontology; networks; spatial point process; data-driven learning; higher education

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Introduction

Fossils are remains of ancient organisms, or their traces, which document diverse aspects of the Earths' history. Fossilized materials-such as shells, bones, and wood fragments-are commonly used as didactic materials for teaching and learning paleontological concepts in formal settings. Researchers and educators, spanning primary to higher education learning environments, have explored the use of physical specimens for teaching and learning different concepts of both the Natural and Earth sciences (Dilcher, 1967; Grant et al., 2016; Macdonald et al., 2005; Martinez & Serpa, 2022; Pimiento, 2015). While the educational value of fossils is widely recognized, teaching practices are still cantered around the use of physical fossil records (i.e., fossil materials) (Figure 1), ignoring the abstracted fossil records (Allmon et al., 2018) that led to major breakthroughs in modern paleobiology research (e.g., Sepkoski 1981; Alroy et al. 2008). Here we aim to highlight a gap between state-of-the-art paleontological research and teaching practices in the classroom by exploring the multifaceted nature of the fossil record, including in-situ and ex-situ physical materials as well as the data and different abstracted representations as educational tools in formal education environments.

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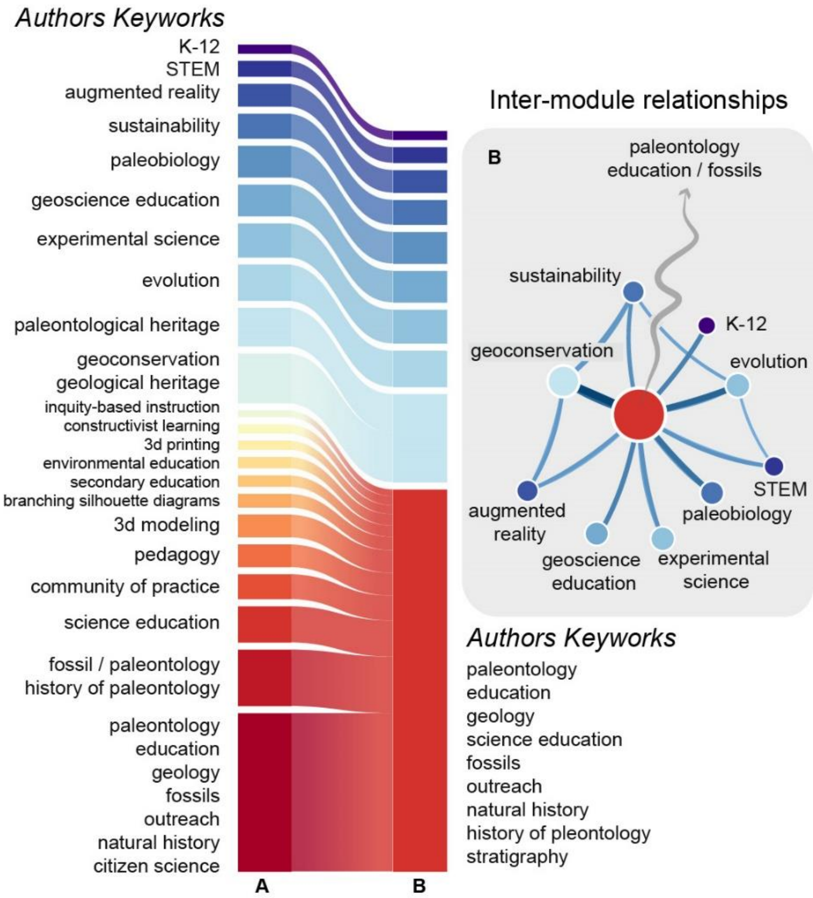

Figure 1. An alluvial diagram describing the major topics addressed in the literature on paleontology teaching and education research**.** It depicts the modular structure of a weighted co-occurrence network of authors keywords in filtered documents from the Web of Science core collection database (WoS). Data: 107 documents retrieved from WoS under the search: (PALEONTOLOGY OR PALEOBIOLOGY) AND (TEACHING OR EDUCATION). The network was built using VOSviewer (Van Eck & Waltman, 2010). After removing names (e.g., personal names, cities, countries, localities) and disconnected words, the input network comprises 191 keywords linked through 586 weighted edges. Because the optimized network partition (A) does not show a hierarchical structure, it was partitioned using varying Markov times models (A = 1 and B = 2) with the Map Equation framework (see Scarponi et al. 2022) to describe its modular organization at different resolutions.

The Multiple Fossil Records in Modern Paleontological Research

A major conceptual change in modern paleobiology research has been the distinction between the physical fossil record, consisting of specimens, and the abstracted fossil record derived from this physical record (Allmon et al., 2018). The concept of the abstracted fossil record was first introduced to highlight the extensive data already stored in large paleontological databases (D. Sepkoski, 2013), concurrent with the ambitious research effort of cataloging the Phanerozoic fossil record (Alroy et al., 2008; J. J. Sepkoski, 1981). This major shift in paleobiology research represents a transition from a specimen-based discipline to its current status as a data-driven field (Dillon et al., 2023). Recently, a new major conceptual change in paleobiology has emerged from network-based studies that characterize network representations of fossil data as abstracted fossil records that can be improved (Rojas et al. 2017*b*; Kocsis et al. 2018; Muscente et al. 2018; Rojas et al. 2019; Kocsis et al. 2021; Rojas et al. 2021; Viglietti et al. 2021; Pilotto et al. 2022). Intuitively, a good network representation of the physical fossil record should be maximally parsimonious yet sufficiently complex to capture the dependencies in the high-dimensional paleontological data. Researchers designing network representations of paleontological data make various assumptions about the structure and dynamics of the sedimentary record, such as whether or not to describe temporal constraints. These

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assumptions impact the outcome of the network analysis, such as whether or not network partitions capture or distort larger-scale patterns (see Rojas et al. 2022). As a result, the same benchmark data, for instance global records of the benthic marine invertebrates in the paleobiology database (Peters & McClennen, 2016), can be represented in different ways, for instance unipartite networks (Kocsis et al., 2018), bipartite networks (Rojas, Gracia, et al., 2022), multilayer networks (Rojas et al., 2021), hypergraphs (Eriksson et al., 2021, 2022), and population networks (Kirkley et al., 2023).

In addition to the network representations of fossil data, point process models describing spatially explicit events, for instance the distribution of individual fossil specimens in the geological record (Mitchell et al., 2015; Mitchell & Butterfield, 2018) or the location of biotic traces on the skeletons of shelled marine invertebrates (Karapunar et al., 2023; Rojas et al., 2015, 2020), are abstracted records that holds considerable promise for data-driven learning (DDL) in paleobiology. A large body of research on drilling predation in shelled marine invertebrates has successfully documented diverse aspects of predator–prey interactions (Kelley & Hansen, 2003; Klompmaker et al., 2015; Kowalewski et al., 1998) in the fossil record. However, taking advantage of the spatial information inherent to the drillholes, the spatial point pattern analysis of traces (SPPAT) (Rojas et al. 2020*b*) introduced a novel set of graphic (i.e., kernel density and hotspot maps) and quantitative tools (i.e., K-function, L-function, MCD), previously used in ecological research, to unlock some spatial information usually ignored in paleontological studies. Karapunar et al. (2023) showed that the SPPAT is transferable to other paleoecologic data such as encrustation (Klompmaker & Boxshall, 2015) and parasite-induced malformations (Fitzgerald et al., 2024; Huntley & De Baets, 2015), allowing for standardized investigation of a wide range of biotic interactions.

A Call for Educators to Leverage the Multiple Fossil Records in the Classroom

Over recent decades, fossil specimens have become essential tools in education, extending their influence from natural history museums to formal educational settings. Educators and researchers across primary, secondary, and higher education levels have embraced the use of fossils, such as shells, carapaces, bones, and wood fragments, to teach concepts in both the Natural and Earth sciences. These physical materials allow students to engage with evolutionary biology, ecological dynamics, and geological processes in an interactive and hands-on manner (Grant et al., 2016; Macdonald et al., 2005; Martinez & Serpa, 2022; Pimiento, 2015). However, the widespread emphasis on fossil specimens, while valuable, reflects only a portion of the multiple fossil records available for education, aligning with contemporary paleontological research (Figure 2).

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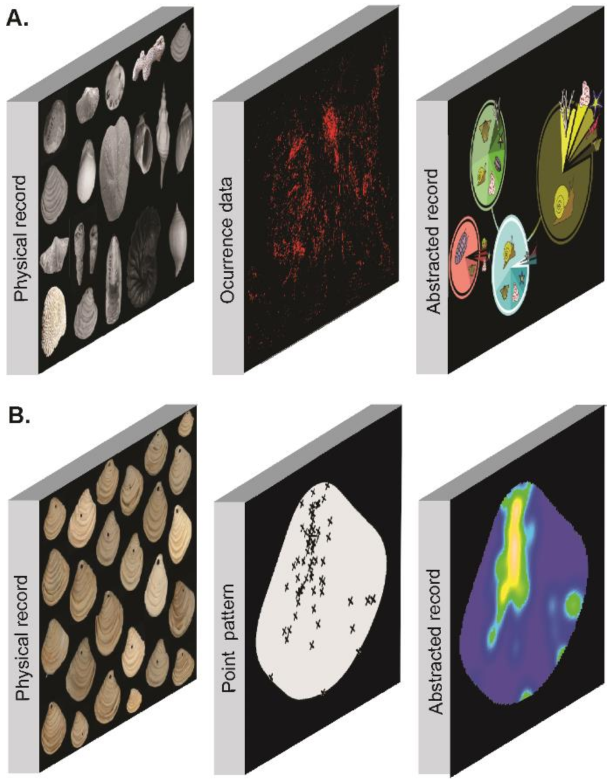

Figure 2. The notion of the multiple fossil records in modern paleobiology research. **A**. The multiples records of the Phanerozoic marine faunas: (left) a selection of fossil representing the core of the benthic marine faunas (i.e., corals, brachiopods, mollusk, echinoderms); (middle) a scatterplot of global records of the Phanerozoic benthic marine faunas in the Paleobiology Database (PaleoDB); (right) the Earth-Life System. It is a multilayer network representation of the global occurrence data with a four-tier modular structure (Rojas et al. 2021). **B**. The multiple fossil records of drilling predation: (Left) Specimens of the bivalve *Lirophora glyptocyma* (Oak Grove Sand Formation, Early Miocene, Florida) representing the physical record; (Middle) spatially explicit data on drillhole locations; (Right) Kernel Density Map of predatory traces around the prey shell. Data on drillhole locations were collected and analyzed using Spatial Point Pattern Analysis of Traces (SPPAT) (Rojas et al., 2020). Adapted from (Rojas, Holmgren, et al., 2022).

Teaching practices in paleontology and related disciplines often overlook abstracted fossil records, i.e., network-based representations of high-dimensional fossil data and (point process models describing spatially explicit events (e.g., community-scale spatial distributions; distribution of biotic traces on shelled invertebrates) that have driven transformative breakthroughs in modern paleobiology (Alroy et al., 2008; J. J. Sepkoski, 1981). These abstracted records offer critical insights into large-scale paleontological patterns and processes that cannot be obtained from physical specimens alone. Moreover, integrating abstracted fossil records into the classroom creates opportunities for interdisciplinary education by linking paleontology to fields like data science, and computer modeling. Such an approach not only enriches students' understanding of the history of Life on Earth but also could provide them with transferable skills and a broader appreciation for the interconnectedness of scientific disciplines. By integrating both physical and abstracted fossil records, educators can foster a more holistic and interdisciplinary understanding of the history of Life on Earth, while also embracing data-driven learning (DDL) in paleobiology. Leveraging abstracted records not only deepens insights into paleontological patterns but can also develop critical skills in data analysis, visualization, and interpretation. This aligns with modern educational strategies that emphasize data literacy as essential for navigating and contributing to contemporary science (Qiao et al., 2024), thereby preparing students to address complex, interdisciplinary challenges.

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