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ORIGINAL ARTICLE

# Fossils on the Market: An Attempt to Characterise the Auction World (2010–2022)

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## Abstract

The collection of fossils supports a thriving market that is largely unknown to the academic community. The fossil market is characterised by fairs, online shops, physical stores and auction sales that attract hundreds of thousands of people each year. The sale of fossils to private individuals is often perceived as a threat by professional palaeontologists, who fear that valuable, maybe unique, specimens are being removed from scientific inquiry. In this paper we explore the global fossil market based on data shared online by international auction houses. We analysed the sales of fossils made by 115 auction houses over a period of 12 years (January 2010 to December 2022) whose auction results were still available online in 2022. Thirty parameters were collected for each auctioned item, including taxonomic identification, provenance, estimates and realised prices, etc. A total of 10.471 records were analysed. The database also includes high profile auction results, such as the Stan auction (*Tyrannosaurus rex* sold by Christie's in 2020 for around 30 million US dollars). Even if many (54%) of the auctioned fossils come from Africa and Asia, only a small minority of the auction houses operates from these continents. These results are useful not only to learn more about the international fossil trade and to provide relevant information to auction houses, fossil preparators and sellers, but also to better assess the economic value of fossils from an insurance point of view, which is useful information for museum and university collections. They also provide a basis to address legal and policy issues of the private fossil trade.

**Keywords** Fossil trade · Non-renewable resources · Auction · Private collection · Palaeontological heritage

## Introduction

Fossils are the sole direct evidence of the evolutionary history of life on our planet. Through the study of the fossil record we can learn about the past diversity of organisms and ecosystems, and this information is unique, unrepeatable and must therefore be protected for future generations along with the other components of what has been called the geoheritage (DeMiguel et al. 2021). Moreover, fossil specimens are a limited, non-renewable resource, regardless of the exact number of specimens available for each taxon (Barrett 2018). Ethical aspects are being applied with increased attention to palaeontological heritage, leading to the recent introduction of the concept of palaeontoethics in the literature (DeMiguel et al. 2021). This concept, which deals with ethical, natural, and social issues is intrinsically complex due to the diverse perspectives one can have on the subject.

While there is widespread recognition of the scientific, historical, and cultural significance of fossils, governments around the world vary greatly in their regulations aimed at conserving and managing their respective national palaeontological resources.

### Fossils: From Scientific Specimens to Collectible Treasures

In many countries fossils are regarded as cultural assets that warrant protection akin archaeological items. In others, they are likened to mineral resources, and their exploitation is governed by mining codes (Kuhn 2022).

Museums, both private and public, are indeed the principal repositories where fossils are prepared, preserved,

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studied, and displayed to the public. However, fossils also attract a large number of enthusiasts, many of which possess a personal fossil collection.

There are a lot of reasons for which a person might collect fossils, including aesthetic value, prestige, curiosity, scientific interest in the geological history of an area or in a particular group of fossils (e.g. ammonites) or, finally, for educational purposes. The acquisition of new fossils by museums and private collectors can occur through direct field collection, donations from other collections, or purchases from the fossil market.

### The Market

The demand for fossils has led to the development of a thriving market, which has prompted the emergence of sellers of palaeontological items professionals who specialise in excavating, preparing, and selling fossils, but has also fuelled illegal trading.

It must be stressed here that not everyone, however, agrees that fossils could be collected for purposes other than scientific research and a hidden, illegal and potentially dangerous market (DeMiguel et al. 2021; Raja and Dunne 2022), that also has its roots in scientific colonialism (Cisneros et al. 2022), has been pointed out (see also Browne & Dashdorj 2022, and Dunne et al. 2022, for issues related to the Burmese, Chinese, and Mongolian issues). Indeed, some palaeontologists even consider private fossil trade as a form of vandalism (Lipps 2009), though others are more compliant, like Barrett (2018) according to which fossils should not be exclusively claimed by scientists as various communities may have legitimate motivations for obtaining and preserving them.

### Questions

But do we truly know what is being sold and purchased in the fossil market? It is indeed challenging to precisely measure the scale and composition of the fossil market due to its widespread distribution and the lack of consistent information on many smaller sales. In fact, there are four main ways for obtaining fossils for a private collection: 1) physical or online stores, 2) trade shows, 3) auction houses, and 4) bartering/buying from other collectors. Given the difficulty of obtaining sales information from fossil shops, amatorial vendors and professional sellers at trade shows, and private collectors, we directed our analysis primarily toward auction sales.

### Fossils at Auction

At auction, fossils can be placed either in the Natural Science section or in the 'curiosities' or art section (e.g. the *Tyrannosaurus* Stan was sold by Christie's in the "20th Century Evening Sale" auction along with a Picasso paint—https://www.christies.com/en/auction/20th-century-evening-sale-29061/). One of the earliest recorded fossil auctions had place in 1820 in London when the lieutenant-colonel Birch sold in an auction his collection of Mary Anning's fossils (see the *Catalogue of the sale of Thomas Birch's collection which was sold in aid of Mary Anning and her family at William Bullock's Egyptian Hall, 15 May 1820—GSL Library collections)*. But remarkable, for its scientific implications, is the sale of dinosaur eggs from an expedition to the Gobi Desert by Dr. R.C. Andrews and his team from the American Museum of Natural History in the 1920s, aimed at funding future expeditions (refer to the Discussion section for further details).

Recently, some auctions have transitioned from traditional venues to online platforms. Both physical and online auctions provide valuable insights into sold items. Fossil auctions have garnered significant public interest, attracting attention from mass media outlets, which have produced articles, blogs, and reviews focusing on this unique market.

The sale of large complete dinosaur specimens such as the *Tyrannosaurus rex* 'Stan' or the *Triceratops* 'Big John' inevitably captivates people of all ages, including both palaeontology enthusiasts and academics. For some segments of the art market, structural econometrics are analysed and provided by companies as Artemundi (https://artemundi.com/auction-analysis/), but the world of the auctions offering fossils is largely unexplored, probably apart from the high-end fossils that can attract investors. In the art world, databases of past auction data are commonplace. Some firms also specialise in comparing the economic value of particular exhibits and offer databases of millions of data points (for example https://www.artnet.com/price-database/; https://www.artsy.net/) or private consultations as a paid service to help prospective buyers understand what they are investing in. However, this does not apply to data concerning the sale of most of the traded fossils, so we had to create a specific database in order to improve our knowledge of the market.

We analysed the sales of fossils made by 115 auction houses over a period of 12 years (January 2010 to December 2022). This choice was dictated by the desire to understand how much the world of the fossil trade has changed over a period of at least a decade, in a time window that we can still regard as the recent past, and to obtain a sufficiently large amount of data to allow us to make meaningful observations. The primary targets of this study are to understand which fossils are being auctioned and sold, whether or not they are of high scientific value and what is the economic value of fossils in the current market.

## Materials and Methods

For this research were collected data (available online in 2022) related to 10,471 fossil sales (both in presence and online) as provided by 115 auction houses. For each sale

30 parameters were recorded and entered in a spreadsheet file. The analysed variables can be divided into two groups: those that refers to the fossil from a scientific point of view and those that relate solely to its sale.

The first group of variables (see below for a description) were coded as binary (presence/absence) attributes according to the information given by the auction houses on the fossil's: 1) systematics (genus, species, plant, invertebrate, vertebrate), 2) stratigraphic and geographic provenance (age, geographic area), 3) preservation (slab, incoherent matrix, nodule, amber, 3D preservation without matrix, whole, partial, trace), 4) preparation (prepared/worked material, restored/restoration indication) and 5) scientific and aesthetic value (fake, scientific interest, museum quality).

The second set of variables, related to the sales, refers instead to the 1) auction houses (auction house name, URL of the auctioned item, location of the auction house), 2) sale (date of sale, sold/not sold, buyer's premium, estimated price, price achieved) and 3) seller/buyer (location of the private seller who consigned the item to the auction house, location of the buyer). To provide a clearer view of the breakdown of the data, we report here the explanation of the analysed parameters or parameter clusters in the same order in which they will be presented in the Results and Discussion sections. Data have been analyzed in an aggregated way.

## Systematic Identification and Distribution

The scientific name (genus and species) is not consistently present among the data the auction houses associate to an offered fossil. When not present, the auction houses identified fossils using a common name (e.g. ammonite) or the term 'unidentified fossil'. In analysing the taxonomic data, we did not attempt to systematically verify the correctness of each single identification provided by the seller or the auction house, as we were mainly interested in investigating how much taxonomic information was provided by the seller. However, a randomly preformed check of a subsample of data indicated that most of the identifications are reliable. To understand what type of fossil is being sold, considering that most of them lack a specific or even generic attribution, we first assigned the fossils to 3 broad systematic categories: invertebrate/vertebrate/plant. These three systematic groups, in turn, were subdivided into a number of more specific subcategories. Invertebrates were subdivided into stromatolites (generally sold along with fossil even if they are sedimentary structures whose origin is mediated by microorganisms), sponges, medusoid or Precambrian organisms, cephalopods, ammonoids, bivalves, gastropods, trilobites, arachnids, crustaceans, insects, and echinoderms. For the subdivision of the vertebrates, it was decided to use the following taxa: chondrichthyans (cartilaginous fish, such as sharks), osteichthyans (bony fish), amphibians, reptiles (including marine reptiles and flying reptiles but excluding dinosaurs), dinosaurs (excluding birds), birds and mammals. It was decided to create this subdivision, which is not strictly phylogenetic, on the basis of the possible greater attraction of certain types of fossils to collectors (also based on the authors' prior knowledge), in order to have a clear division among the fossils sold and therefore in order to better evaluate the results. Trace fossils (ichnofossils) were assigned to the corresponding systematic category and subcategory based on the supposed identity of the trace-maker as reported by the auction houses.

## Geographic Origin

To standardize the geographic information, only the continent of provenance of the fossils was considered. Russian fossils were referred to either Europe or Asia when the locality was available or when, according to our experience, it was possible to assume their origin with relative precision. Fossils from Mexico and Central American countries were pooled with those from South America.

## Age

Even though some fossils were dated with some precision by the seller (Late Miocene, for example), in most of the cases we were unable to verify the reliability and accuracy of the geochronologic information provided with the auctioned fossils. To simplify the analysis of the data, the age of the fossil, when reported, was collapsed to the Era (Cenozoic, Mesozoic, and Palaeozoic + Precambrian).

## Type of Preservation

The preservation mode was coded using eight categories, that refer to the type of fossilization (slab, nodule, amber, 3D without matrix or included in incoherent matrix) and the completeness of the fossil (whole, partial). A further variable indicates whether the item represents a fossil trace left by the organism (ichnofossil) or a so-called body fossil.

Slab (Fig. 1a) refers to a fossil preserved as a flat remain occurring on the surface of a hard rock stratum (e.g. limestone). Incoherent matrix (Fig. 1b) is when the fossil is embedded in a relatively soft rock, such as shale or sandstone, from which it might also be extracted during preparation, or exposed on the surface. A nodule results from a special diagenetic process occurred around the remains of the organism during fossilization, that gives it a pebbly coating. Amber is the fossil resin of conifers that might include both plant and animal fossils of various species. It was decided not to distinguish between amber and copal, a fossil resin with a lower degree of polymerization, given that the fossil inclusions are similarly preserved in both type of material.

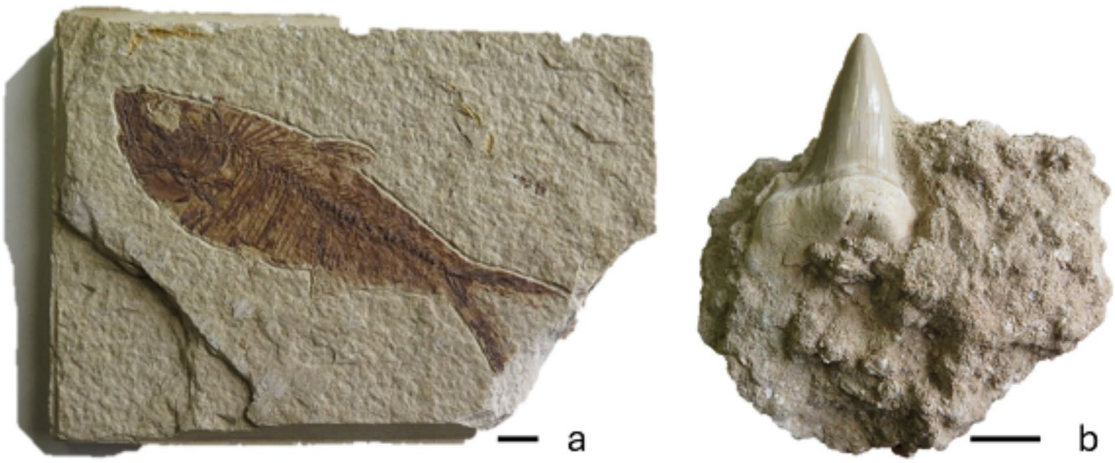


**Fig. 1** Examples of frequently traded fossil items. **a** *Knightia eocaena* on slab from Wyoming, **b** *Otodus* sp. on incoherent matrix from Morocco. Scale bar 1 cm

A body fossil has been considered as whole if at least 80% of it was preserved. Therefore, a single valve of a bivalve, an isolated tooth or bone or a cluster of just few elements of a skeleton, were considered as partial. Some fossils also preserve impressions of 'soft parts'; these, however, were not considered in determining whether the specimen was whole or partial because of the rarity of this type of preservation.

## Worked Material, Museum Quality, Fake and Other Aesthetic Attributes

Aesthetics, the workmanship of the fossil if prepared, and the scenic presence are not considered priority elements in determining its scientific value by palaeontologists (unless the fossil has to be displayed in museum), however, they are important elements that attract the buyers and eventually affect the sale price. For this reason, this type of information was also considered in this study. To indicate that the fossil was clearly manipulated (through polishing or other processes) purely and exclusively for artistic or decorative purposes, we used the definition 'processed/worked material' (Fig. 2).

One definition widely used in the fossil market is 'museum quality'. This is not to be confused with scientific significance; it is purely an aesthetic judgment, often used by fossil sellers and buyers to indicate that a fossil may be whole, beautiful, aesthetic. Rather than recording whether the seller used this label for a given fossil, we attributed the “museum quality” label to those fossils that were considered outstanding in terms of aesthetics, completeness, workmanship and visual impact. As far as the scientific value of a fossil is concerned, we arbitrarily considered a fossil offered at an auction as “scientifically interesting" or "not scientifically interesting” on the basis of our personal experience, by subjectively evaluating its rarity, completeness and association with stratigraphic and geographic data.

Another important piece of information we evaluated is whether the fossil was evidently restored (reconstruction of missing or broken parts) and if there was an indication of restoration in the description provided by the seller. A specimen was considered to be a fake if no restorations are mentioned in the description of the fossil, but restorations or reconstructions are visible on approximately more than 40% of the fossil (Demeulemeester and Stein 2022). The transparency of this data is important on a scientific level, but also as a matter of fairness to the buyer.

## Number of Auction Houses, Their Geographic Locations and Sale Date

The name of the auction house was noted for all the auctioned items, also for those offered by the aggregator LiveAuctioneers. The URL for each offered item was also recorded, as well as that of the auction house that offered the fossil. The geographic location of the auction house was noted. The auction house Catawiki also provided the location of the private seller that consigned the item.

The date of sale is represented, when available, by the full date (day-month-year). In some cases, especially for older auctions, only the year of sale was available. It should be noted that for the highly active online auction house Catawiki, we could only gather sales data for the current year of the analysis (2022), because its online platform does not retain an auction history. Although the data did not allow us to analyse the historical variation in trade for this particular auction house, it enabled us to obtain valuable information, such as the provenance of the seller and buyer of the fossil (the high profile auction houses do not share this type of information in order to protect the privacy of the client, who can choose to be anonimus or not).

**Fig. 2** Example of a processed/worked material made of fossil wood that is incorporated into a piece of furniture

### Number of Items Offered and Sold Per Year

Some auction houses provide information only for items sold, while others offer a list of both sold and unsold items. For the purposes of this work, data from both types were collected. If a fossil is put up for auction but remains unsold, it may be offered to the public again according to rules that vary between auction houses. As a result, the same item may appear multiple times within our dataset. Auction houses have different policies regarding the possibility of listing the same fossil more than once (e.g. Catawiki allows the seller to list the same fossil online a maximum of 2 times, whereas Sotheby's allows to exhibit the same fossil only once a year).

### Buyer's Premium and Achieved Price

The buyer's premium is a component of the sale that is not purely palaeontological but is of primary interest to buyers. A buyer's premium is an additional fee imposed by the auction house, paid by the buyer on top of the hammer price. This premium is retained by the auction house and is not transferred to the seller (Maclaren 2017). When explicitly indicated in the sale record, the buyer's premium was recorded along the achieved price. The indication of the buyer's (usually shown on the auction website) is at the discretion of the individual auctioneers. In our analysis we decided to use the achieved price inclusive of the buyer's premium, as this is the real amount paid by the collector or museum for the fossil.

The achieved price was reported in British pounds, dollars (American, Hong Kong, Canadian), and euros. To standardise the sale data all currencies have been converted into euros according to the following exchange rate:1$ = 0.92€, 1$Hong Kong = 0.12€, 1£ = 1.14€ (updated to November 2023).

### Comparison Between Auction Houses

The number of fossils sold in a single year (2022) by Catawiki, exceeds the total number of items sold by all other auction houses combined over the 12-year period we analyzed. For this reason, we decided to keep the data relative to the Dutch auction house separated from that of all the other auction houses (OAH) considered in our study.

### Supplementary Information

A breakdown of the sale data for four main fossil groups, namely ammonites, chondrichthyans, dinosaur, and plants, is provided in the supplementary information (SI). Ammonites are the most auctioned invertebrate fossils, chondrichthyans are the most auctioned vertebrate fossils, dinosaurs, while not the most auctioned fossils, are the ones that generate the greatest financial gain from their sale, and finally plants were chosen as a counterpart to animal fossils (Fig. 3). The whole database is available upon request to the corresponding author.

## Results and Discussion

### Systematics Identification

The auctioned fossils were identified with varying degree of precision. In some cases, the identification was limited to higher Linnean categories, such as class (e.g.: reptile or "fish"), but in most cases, the genus was reported (82%). The indication of both the genus and the species was present in 52% of the cases. Only 18% of the fossils lacked any form of systematic identification.

The percentage of specimens associated with a genus indication remained relatively constant over the 12-year

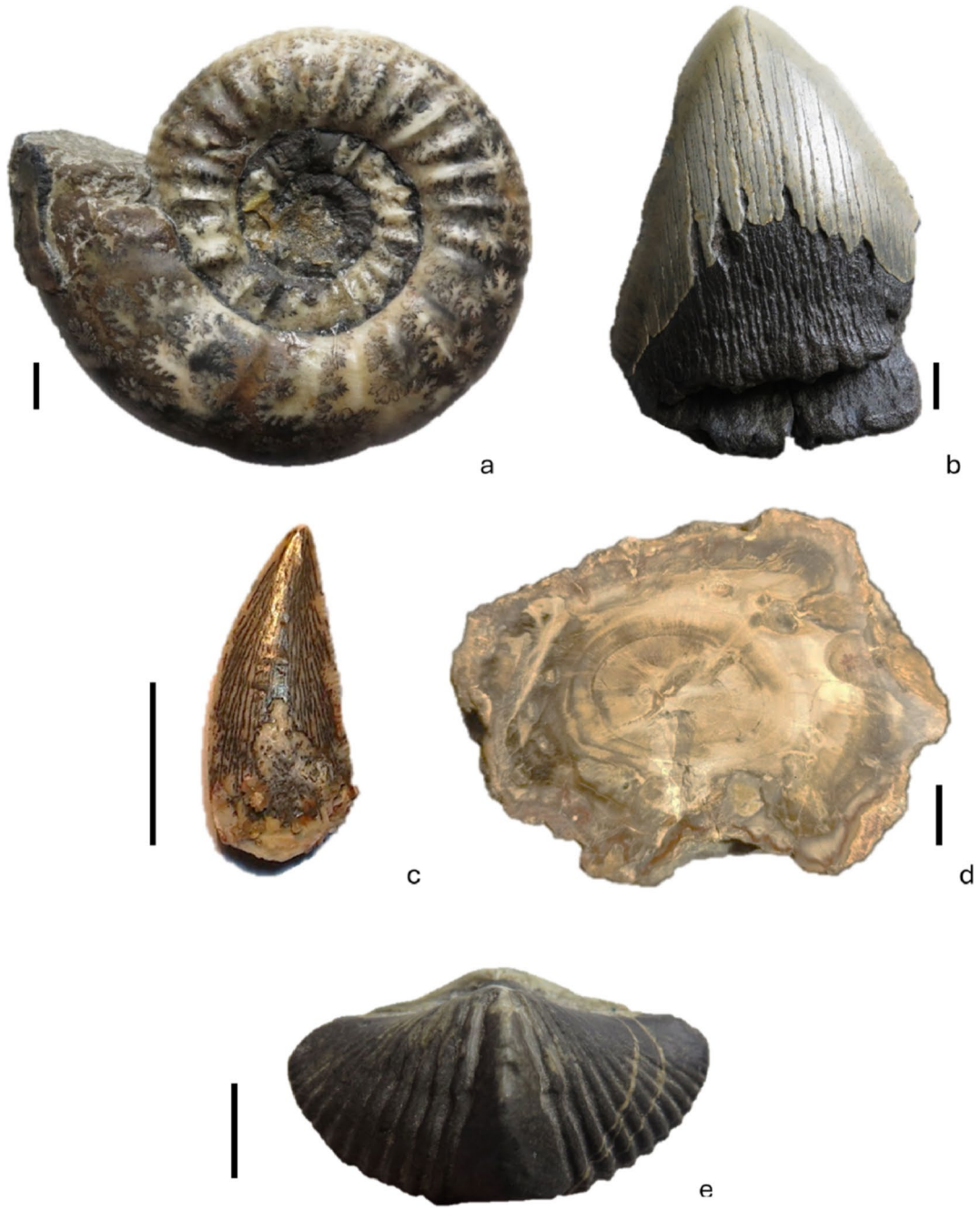


**Fig. 3** Examples of frequently traded fossil items **a** *Pictonia* sp. (ammonite); **b** *Otodus megalodon* tooth (chondrichthyan); **c** abelisauroid tooth (dinosaur), **d** fossil wood (plant), **e** *Spirifer* sp. (brachiopod). Scale bar 1 cm

interval examined, ranging between 69 and 90%. (Fig. 4). Specimens identified at the species level were far less common and their percentage showed somewhat greater variability over time. In eight of the 12 years analysed, only 50% or fewer of the auctioned items had a specific identification.

The lower number of specimens identified at the species level can be due to the lack of experts of particular fossil groups available to the auction houses, the incompleteness of the fossils or its over-restoration or more simply a lack of interest by the sellers and the auction houses in pursuing detailed identification, as this is a time-consuming activity.

We also discovered some significant errors in the identifications. For instance, a *Claudiusaurus* (a Permian marine reptile from Madagascar) was listed as a *Keichosaurus* (a Triassic sauropterygian reptile from China). Although it was not possible to check in detail each of the fossils analysed,

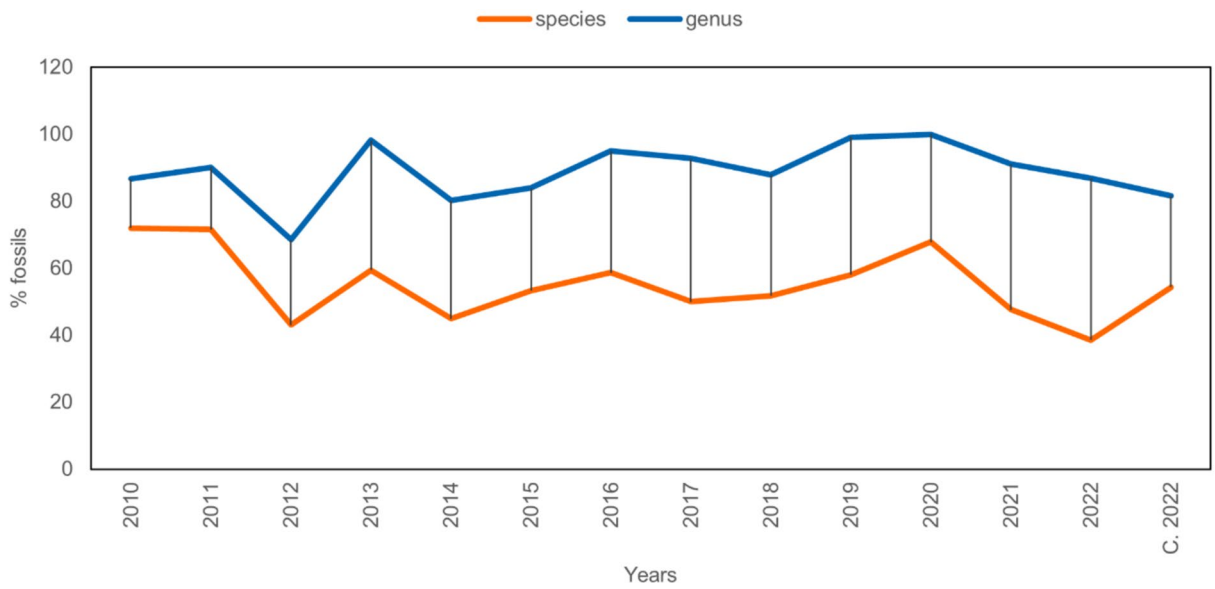


**Fig. 4** Percentage occurrence of genus (blue) and species (orange) identification over 12 years, with data from Catawiki for 2022 only (indicated as C.2022)

the identification seemed to be generally correct, and a careful check of 100 randomly selected items revealed no errors in the systematic attribution, suggesting that misidentification are likely less than 1%.

## Systematics Distribution

Of the total fossils auctioned, 39% were invertebrates, 49% were vertebrates, and 12% were plants.

Among the invertebrates (3921 items; Fig. 5): 36% were ammonites, 20% trilobites, 14% echinoderms, 9% insects, 6% other cephalopods, 5% crustaceans, 4% bivalves, 2% gastropods, 1% corals, 1% arachnids, 1% jellyfish and Precambrian organisms, and fewer than 1% were brachiopods, stromatolites and sponges.

Of the 5121 vertebrates auctioned, 34% were chondrichthyans, 24% dinosaurs, 15% were non-dinosaur reptiles, 13% were mammals, 12% were osteichthyans, whereas amphibians and birds amounted each to 1%.

Nearly half of the fossils sold through auctions were vertebrates, with (non-avian) dinosaurs and shark teeth representing more than 50% of the vertebrates. Among invertebrates, the most sought-after groups were ammonoids and trilobites which are abundantly represented in the fossil record, readily available on the fossil market, and relatively inexpensive. Ammonoids and trilobites, in particular, are iconic fossils that being the remnants of extinct organisms embody the "idea of a fossil" in the mind of enthusiasts. Their popularity, along with that of dinosaurs, is likely due to their great diversity in shape and size, and the sheer beauty and "exoticness" of some of the species, making them perfect ideal display items. Interestingly, brachiopods, small clam-like marine animals, despite being scientifically valuable as index fossils, and highly diverse in shell morphology, account for less than 1% of auctioned fossils. This might be because brachiopods are not well-known to the typical auction buyer, who is generally interested in "popular" fossils.

For example, nearly 10% of auctioned fossils (especially at Catawiki auction house), are fossilized insects, particularly those preserved in amber, likely due to the influence of films like Jurassic Park.

## Geographic Origin

The geographic provenance of the fossils was reported in 92% of the cases: 35% of the fossils came from Africa, 20% from North America, 19% from Asia, 18% from Europe, 1% from South America, and fewer than 1% from Oceania (Fig. 6). Most North American fossils were from the United States, particularly Wyoming (osteichthyes and dinosaurs), Florida and California (megalodon teeth), and Arizona (fossilised wood). African fossils were primarily provided by Morocco (trilobites, echinoderms, reptiles, and dinosaurs), Madagascar (osteichthyes, reptiles, and fossilised wood), and Niger (dinosaurs). Concerning Asian fossils, a considerable percentage come from Indonesia (fossilised wood and, most of all, megalodon teeth).

Only 8% of the total fossils auctioned by all auction houses lacked a provenance indication, though it must be

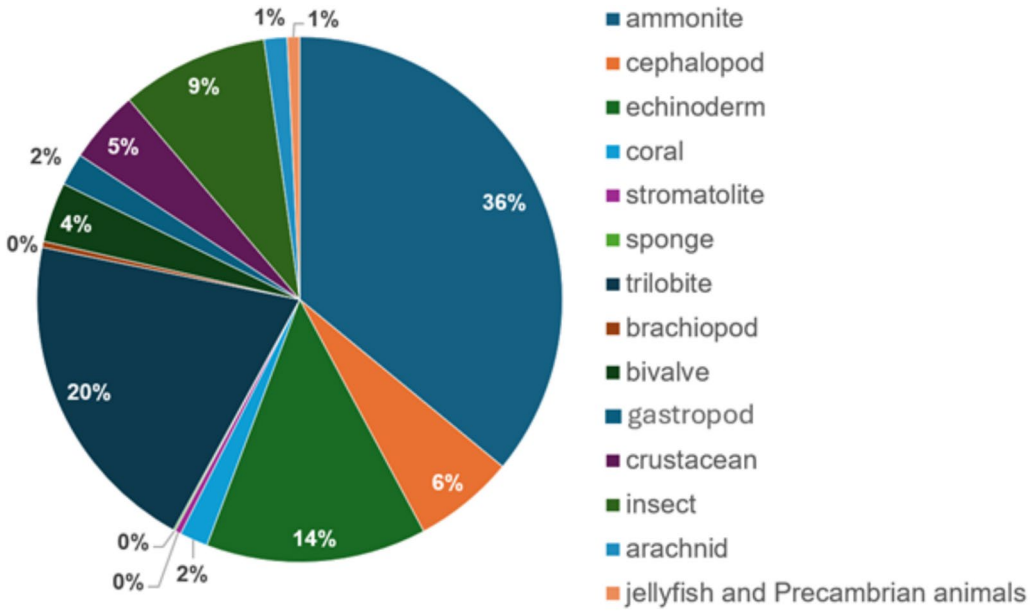


**Fig. 5** Percentage of the different invertebrate groups auctioned

stressed that the percentage of fossils presented with no provenance indication varied greatly between Catawiki (3%), and OAH (16%).

In the majority of the cases, the country or the continent of origin of the fossils was provided. The precise site of provenance was however reported only in a few instances. These cases usually involved well-known fossil localities, such as Solnhofen (Germany) or Hell Creek (USA), where the mention was probably considered by the seller to increase the interest of the buyers in the fossil item. But in most other cases, geographic information was very general, typically referring to the country of origin if not just the continent.

Interestingly, Catawiki and OAH differ in the percentage of fossils sold with regard of their provenance (Fig. 7). African fossils represented 45% of the items auctioned by Catawiki, but only 18% for OAH, for which the main area of provenance of the auctioned fossils was North America (43%). By contrast, only 18% of Catawiki fossils were North American. On the other hand, the proportion of fossils from Europe, South America and Oceania was similar in Catawiki and OAH.

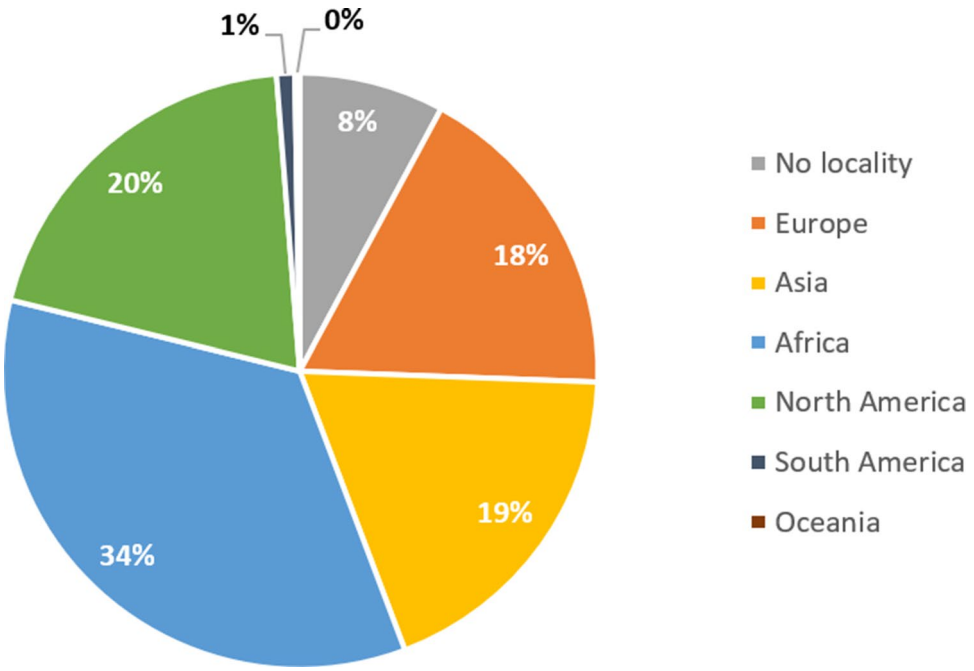


**Fig. 6** Percentage of the geographic provenance of the fossils

The indication of the locality of provenance is generally indispensable for a scientific study and for museum collections but not necessary for the sale of the finds to private collectors. However, the indication of provenance is a fundamental requirement to contrast the illegal marketing of fossils from countries where their sell is not allowed. In this respect, every auction house has a Code of conduct (e.g. Sotheby's Code of Business conduct 2021) that makes the auction of illegally exported fossils very unlikely. However, fossils from areas where trade is strictly forbidden, such as Mexico, Brazil and China (Cisneros et al. 2022), might appear at an auction in the case of the sale of old collections (containing fossils that might still be exported) or to special concessions made by the countries of origin, though this cannot be evaluated on the basis of the retrieval and analysis of the sole auction results. Marocco represents a special case as the country recently decided to apply some restrictions on the trade of national fossils (Lebrun 2020), mainly concerning complete vertebrate skeletons, while common fossils such as trilobites, or mosasaur teeth and isolated bones can still be legally traded and inf act are very common at auctions.

Amber makes up only 3% of the total fossils auctioned in the studied period, with 48% arriving from Myanmar, 36% from the Baltic coasts, and 13% from Central America. In 2021, the SVP (Vertebrate Palaeontological Society) recommended strong embargos on the international trade of Burmese amber, as it was used to finance armed groups. However, we cannot be sure from the data in this research that any change occurred in this regard: auction houses were already rarely selling products from this area. Catawiki actually auctioned some Bourmese amber in 2022, however since we do not have any data before 2021 for this auction house, we cannot affirme wheather there has been a decrease in sales after the SVP proposed embargo (and, most of all, when the amber was collected).

## Age

Most of the items offered (93%) were assigned an age, with the majority from the Mesozoic (42%), followed by the Cenozoic (35%) and the Palaeozoic and Precambrian (16%).

Considering the percentages by year of items associated to a geological age, the age trend of the fossils from all the auctions is fairly constant. The only parameter that varies over time is the percentage of fossils that do not have a time indication. In fact, about 30% of the fossils sold in 2012, 2021 and 2022 do not have an indication, but from 2013 to 2020 the lack of indications is between 5 and 20% (Fig. 8).

Although the geological age of a fossil is crucial at the scientific level, the presence or absence of this information does not seem to affect the appeal of auctioned items. The percentage of sold fossils compared to total auctioned items, is similar between dated (71%) and undated fossils (74%).

## Type of Preservation

Of the total fossils auctioned in the 12-year period examined, 59% were 3D specimens without a matrix. Among the items embedded in a matrix, 30% were slabs, 6% were in an incoherent matrix, and 2% were nodules. Amber and cabochon (polished, gem-like fossils) accounted to 3%.

Fully prepared, 3D fossils remained the most preferred type of preservation among auction buyers. For vertebrate skeletons, this type of preservation allows for particularly effective preparation and mounting. On the other hand, the percentage of fossils on slabs (Fig. 9), steadily decreased over time, from 44% of auctioned fossils in 2010 to 18% in 2022 (Catawiki 28%), except for 2016, when the sale of fossils on slabs peaked to 48%.

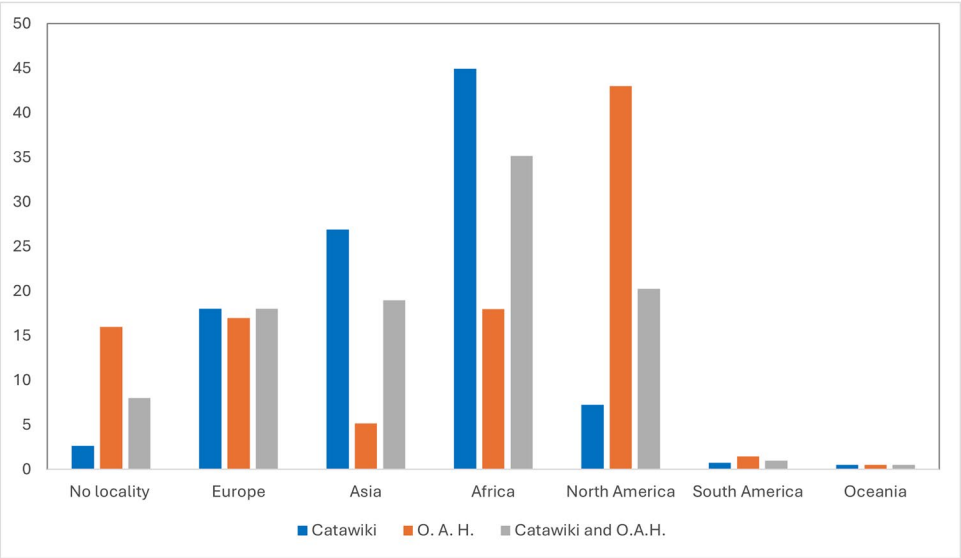


**Fig. 7** Percentage of the geographic origin for Catawiki, for the OAH and in total

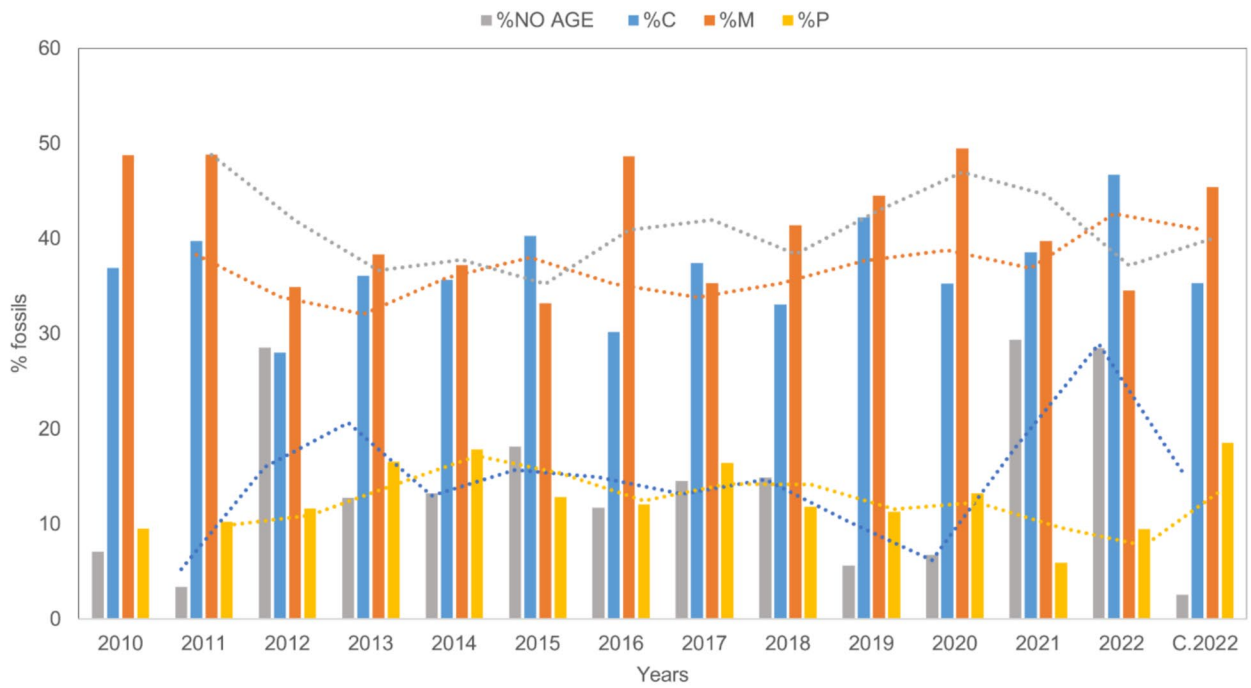


**Fig. 8** Graph showing the number of fossils auctioned over time, specifying the data related to the Catawiki auction house (indicated C.2022)

The amount of auctioned fossils in amber did not vary much over time, ranging from 0 to 3% at OAH and around 5% at Catawiki.

Of the total fossils examined, 60% were classified as incomplete or partial, 39% as complete, and 1% as ichnofossils. Between 2013 and 2020, the number of complete and partial fossils auctioned was comparable in terms of perceived quantity (Fig. 10). However, beginning in 2021, there has been a noticeable decline in the number of complete fossils auctioned compared to incomplete ones, observed in both OAH and Catawiki auctions.

## Quality Museum, Fake, Worked Material and Other Aesthetic Features

53% of the fossils auctioned were considered to possess museum quality, as determined by the authors' expertise. Data from 2012 indicates that museum-quality fossils constituted between 41 and 75% of auctioned specimens (see Fig. 11). However, by 2020, there was a noticeable decline in the proportion of museum-quality fossils, with the figure dropping to as low as 40%. This data suggests that over half of the auctioned fossils lacked the requisite characteristics for museum or exhibition display, although they may still hold appeal for collectors because of various reasons. It is important to note that the overall museum quality of fossils has not uniformly diminished over time, particularly when considering the most significant fossil groups. While a general decline in museum quality is evident across most categories, plants are an exception to this trend. Currently, there is an increasing prevalence of spectacular specimens that garner high media and public attention. Nonetheless, the presence of one exceptional specimen is insufficient to counteract the observed decline in quality among the majority of auctioned items.

Only 1.5% of fossils were deemed scientifically significant. Additionally, 0.7% of the total items auctioned were identified as fakes, while 48% of fossils were reported to have undergone major restoration, based on explicit statements by the auction house. The years with the highest reported restorations were 2011 and 2020, with 6% and 8%, respectively, whereas in other years, the percentage of explicitly declared restorations was 2–3%. However, auctioneers noted that undeclared restorations are common, although they never exceeded 18% of the fossils auctioned annually.

The auction house Catawiki disclosed that at least 10% of its fossil offerings had undergone some form of restoration, which is the highest reported percentage. Furthermore, 17% of the auctioned items were fossils that had been worked into raw materials for furniture, ornaments, and other decorative items, a percentage that appears to be steadily decreasing. The majority of these worked fossils were fossil woods (used for tables and other furniture), ammonites, and fossil ivory, with 16% of the total number of fossils in Catawiki auctions being worked. Amber, which is used to create jewellery and other objects, accounted for 5% of all auctioned amber fossils (Fig. 12).

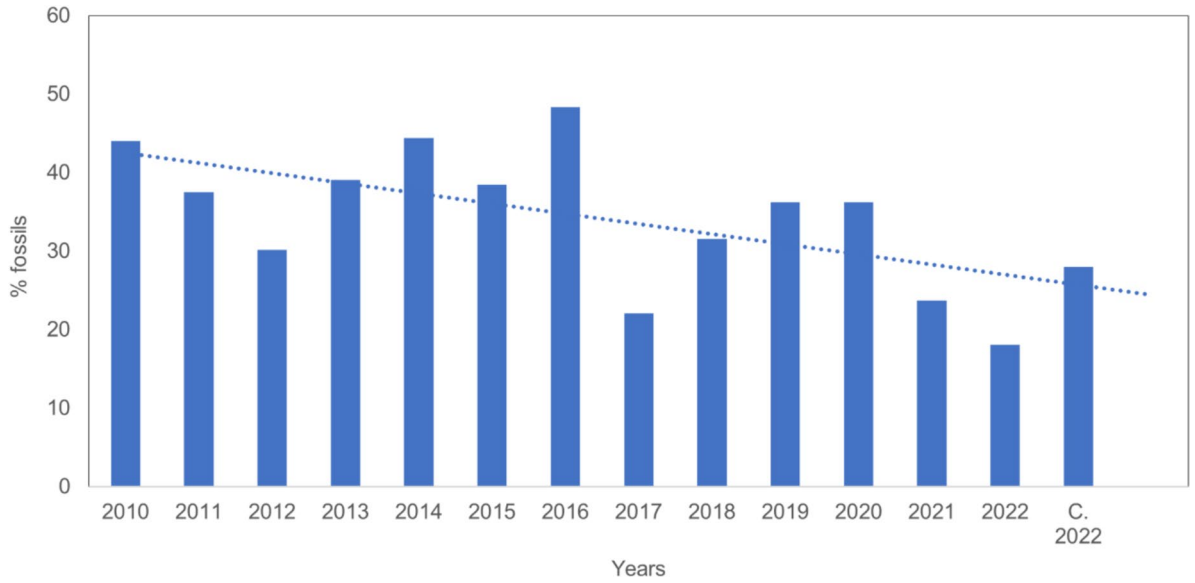


**Fig. 9** Percentage of fossils on slabs auctioned over time, specifying the data related to the Catawiki auction house (indicated as C. 2022). Dot line is linear prevision

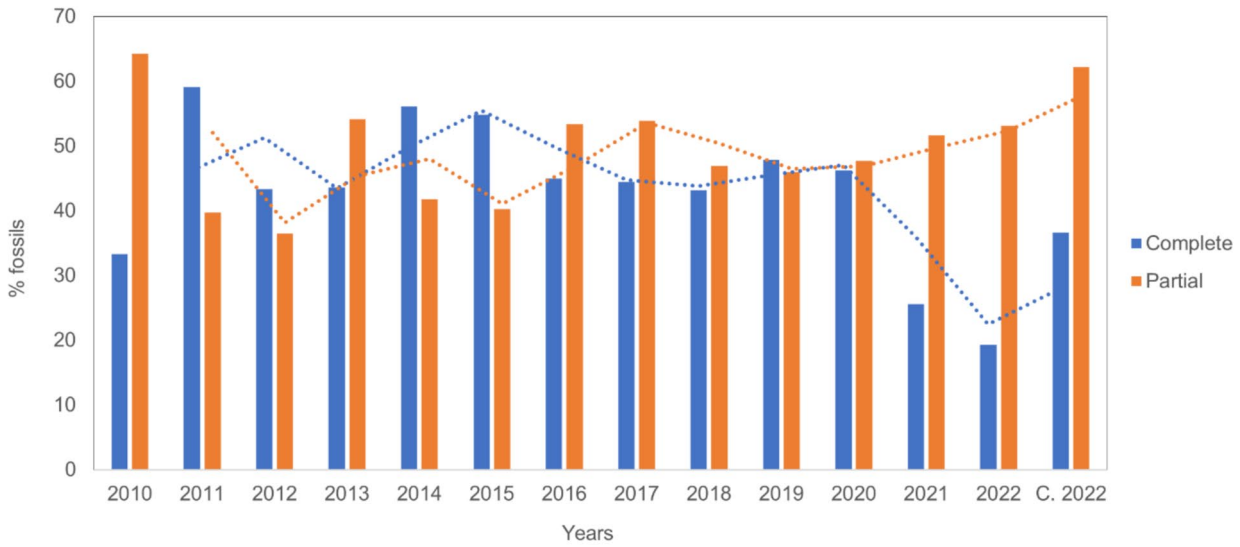


**Fig. 10** Percentage of fossils auctioned complete and partial over time, specifying the data related to the Catawiki auction house (indicated as C.2022)

## Number of Auction Houses and Their Geographic Location

The data analysed in the present study were provided by 115 auction houses, listed in Table 1 (supplementary material), most of them aggregated by the platform LiveAuctioneers.

We must stress again that the data from the online auction house Catawiki were available only for the year 2022 at the time of our analysis, even though this company started to trade in 2008. Despite this, this particular online auction house auctions off so many fossils that in 2022 alone they auctioned off at least 6664 fossils and sold 60% of them (2722 fossil remained unsold).

Most of the auction houses we detected (87%) were in the United States (101), followed by the United Kingdom (7), other European countries (5), and Asian countries (3) (Fig. 13). After noticing this fact, we searched through other auction aggregators, specifically selecting auctions located

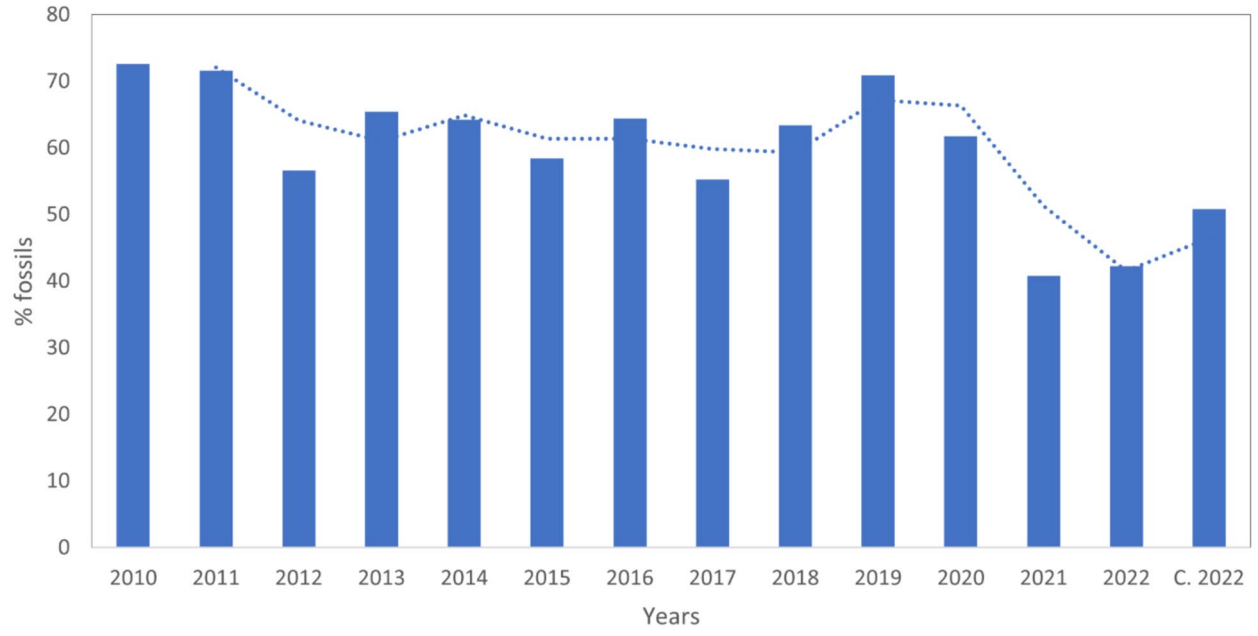


**Fig. 11** Percentage of museum quality fossils through the years, specifying the data related to the Catawiki auction house (indicated as C.2022)

in the Asian continent, South America and Oceania, but no new results appeared, despite the targeted search for terms, that appear very frequently in the auction world, like 'fossils', 'dinosaurs', 'megalodon' and 'trilobites'.

Data show that the market is mainly run by 'Western' dealers (American and European), but buyers may come from all over the world, even if very few are from South America, Africa or Asia (otherwise one might think that this market would have flourished in these places as well). However, it should not be forgotten that the purchase of fossils of particular economic importance can also be a status symbol, a symbol of wealth (although, as we shall see, this is not always the case),

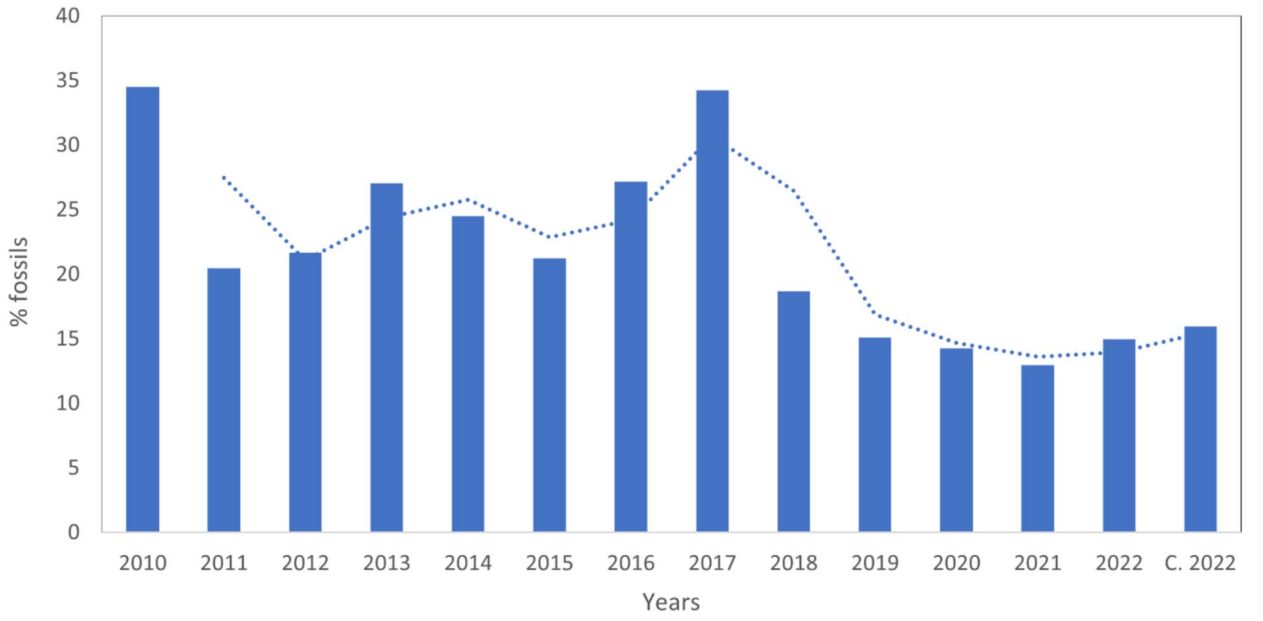


**Fig. 12** Percentage of worked material over time specifying the data related to the Catawiki auction house (indicated as C.2022)

**Table 1** Percentage of fossils dealers' location operating through Catawiki

| Countries | % dealers through Catawiki | Countries | % dealers through Catawiki |
|---|---|---|---|
| Spain | 23,96 | Portugal | 0,91 |
| Nederland | 19,44 | Austria | 0,58 |
| Italy | 15,71 | Hong Kong | 0,55 |
| France | 12,78 | Estonia | 0,31 |
| Germany | 11,43 | Switzerland | 0,10 |
| Taiwan | 3,64 | Hungary | 0,06 |
| Belgium | 3,22 | United Kingdom | 0,04 |
| Poland | 2,58 | Uruguay | 0,03 |
| USA | 2,19 | Slovenia | 0,03 |
| Lithuania | 1,27 | Malta | 0,01 |
| Singapore | 1,11 | Japan | 0,01 |
| | | Sweden | 0,01 |

and certainly participating in the largest European and North American auctions can be an experience in itself for a few people, apart from the fact that European auctions (which have been active for centuries) bring with them an idea of quality and attention to the customer (which, if one is going to spend large sums of money, can give the buyer extra security).

Catawiki auctions alone more than 300 fossils per week, which generates a large amount of sale data (about 10000 data per week). Given the large amount of time needed to process these data and the temporary availability of Catawiki auction results (see Material and Methods), it has been impossible to collect data for all the sales made by Catawiki in 2022 and therefore the results related to this very active auction house must be considered as partial.

Only Catawiki explicits the name of the seller (with the company name if the seller has a company that sells fossils, or simply with a code for occasional private sellers) and its location from where the fossil was sold or shipped. In this case 24% of the fossils sold were exported from Spain, 19% from Holland, 16% from Italy, 13% from France and 11% from Germany (Table 1). Sellers located in the States shown in the following graph with a percentage of 0% sold less than 1% of the items for which the country of the seller is known.

With the exception of 5% of fossils exported by Asian dealers (Taiwan, Hong Kong, Singapore, Japan) and 2% from the United States, the origin of the other dealers is European. The only South American country that exported fossils was Uruguay (but still less than 1%) (Fig. 14).

The auction house Catawiki has made the nationality of the buyer available in its auction results since August 2023. In order to broaden the analysis, it was therefore decided to randomly select a group of buyers (in this case 1440 sales) to analyse where the fossils purchased were exported to. It could be observed that the buyers were in 34 different countries, 77%

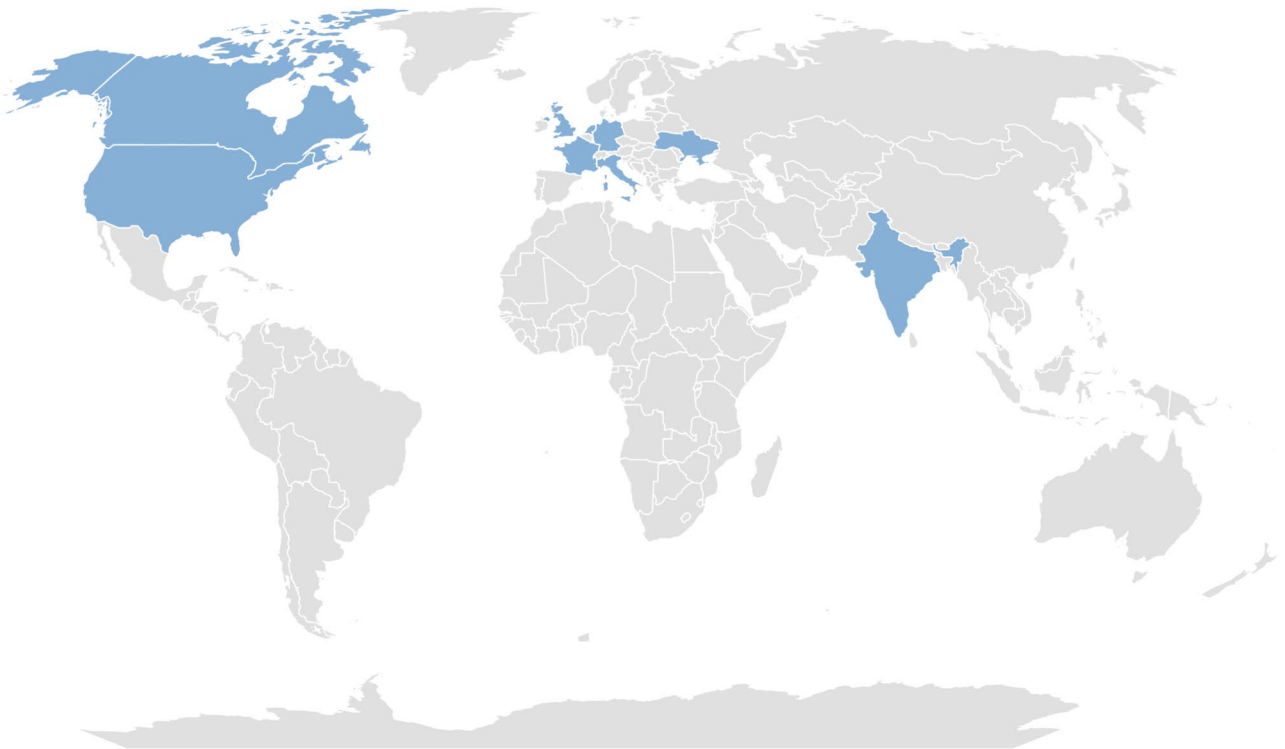

**Fig. 13** Planisphere showing the countries in which the auction houses analysed in this study are located

of which are in Europe, but also in Asia and the Middle East (Japan, Hong Kong, Israel, Singapore, Tajikistan, Turkey, Taiwan) and in America (United States of America) (Fig. 15).

In percentage terms, 15% of the fossils were imported in the Netherlands, the same number in France, 14% in Italy and 8% in Germany. Among Asian countries, 2% were imported in Taiwan, 1% in Hong Kong, and smaller percentages in other countries (Table 2). The United States imported only 3% of the fossils sold by the Dutch auction house.

More than 90% of fossils auctioned by Catawiki are offered from sellers located in European countries, a fact that is not surprising considering that this platform is based in The Netherlands (and is perhaps better known and advertised in Europe than in other continents), but, nevertheless, sellers and buyers can be located anywhere in the World. However, only 17% of the fossils auctioned are of European origin. This gives us an insight into the fact that those who sell fossils are mainly European, but not necessarily those who have extracted the fossils from their places of origin and traded them. Furthermore, it is not uncommon for dealers from different countries to work together (e.g. Moroccan dealers and European dealers), but this is not something that can be ascertained through our research.

As far as the import of fossils is concerned, the collector-buyers of the Catawiki auction house are concentrated in Europe. Although only a quarter of the data provided by Catawiki has been analysed, there are many more buying countries (34) than exporting countries (23). The only countries that are both exporters (albeit in minimal quantities) and importers are Slovenia, Lithuania and Uruguay. These data are important because they allow us to understand that fossil collecting is not only associated with the largest European countries, where there is already a strong tradition of collecting, but that enthusiasts can also be found in countries from where fossils are not exported.

## Number of Items Offered and Sold Per Year

The number of items offered per year has varied substantially over the period studied. For 2010, we found in our data collection (run in 2022) that 84 fossils were auctioned by all the auction houses considered, with an upward trend over time to 642 fossils auctioned in 2022 (excluding the 6664 fossils auctioned in 2022 by Catawiki alone; Fig. 16).

Redundancies, due to the offer of the same fossil item at auction several times (because unsold or sold another time from a buyer who won the fossil in a previous auction) were not eliminated because they could potentially provide additional data for understanding variation in preference toward a certain type of fossil.

The total number of fossils sold through the auctions analysed is 7264 out of 10,471 (69%). The year in which most of the sales were made was 2022, both considering the high number of fossils auctioned by Catawiki and ignoring them.

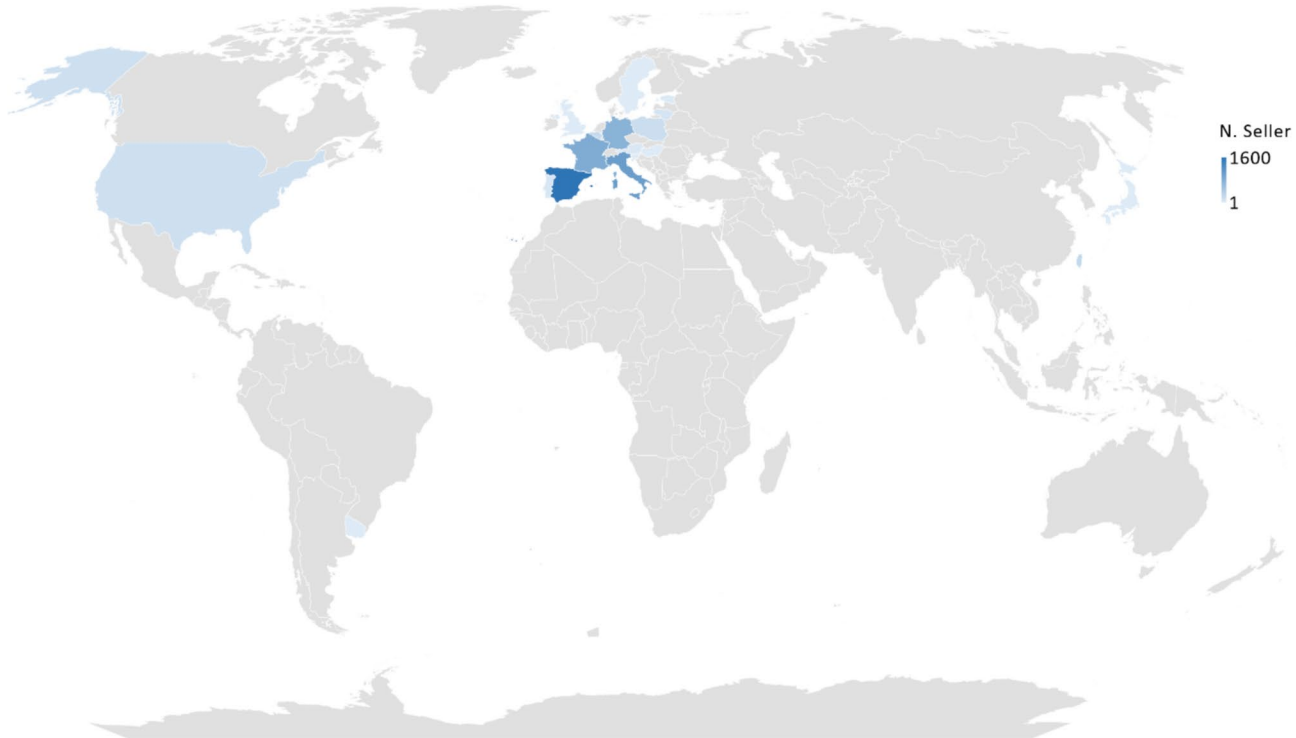


**Fig. 14** Fossils dealers' location operating through Catawiki

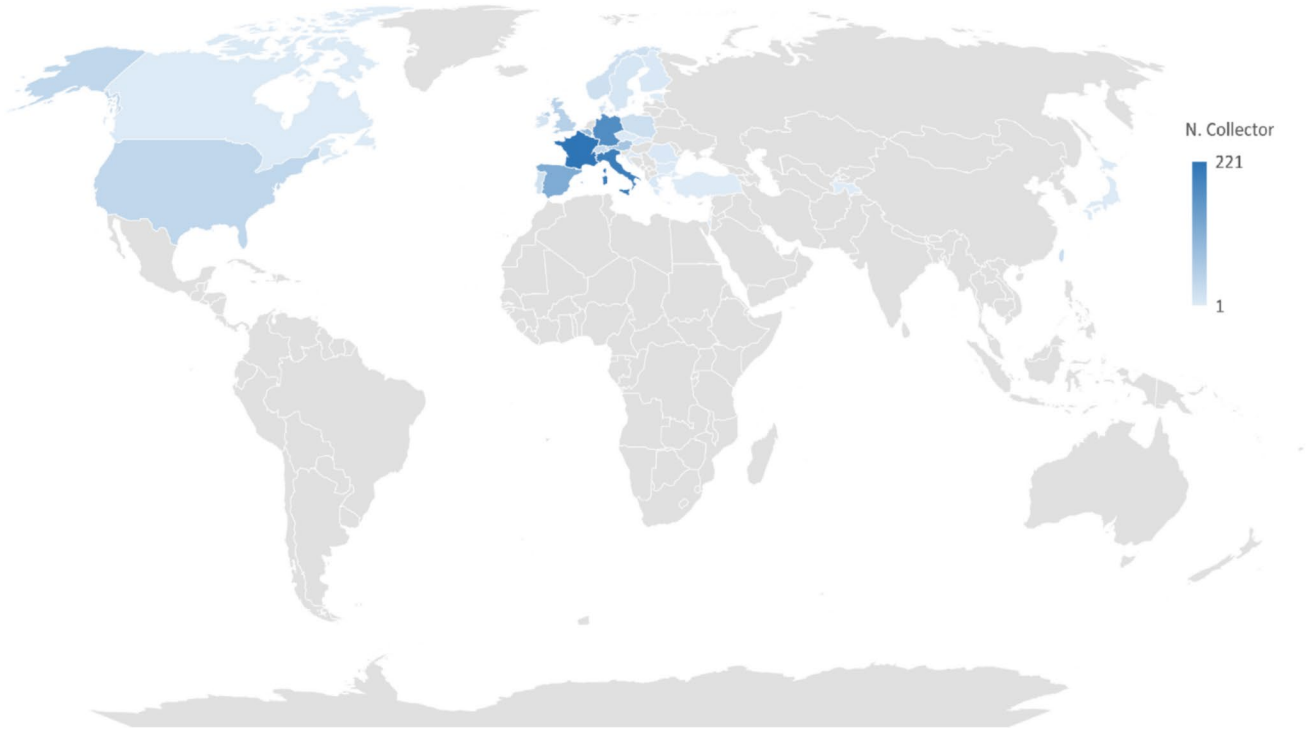


**Fig. 15** Nationality of fossil collector show by Catawiki

**Table 2** Percentage of fossils buyers' location operating through Catawiki

| Countries | % buyers through Catawiki | Countries | % buyers through Catawiki |
|---|---|---|---|
| France | 15,45 | Hungary | 0,84 |
| Nederland | 14,83 | Sweden | 0,77 |
| Italy | 14,27 | Croatia | 0,42 |
| Germany | 12,31 | Finland | 0,42 |
| Spain | 8,46 | Greece | 0,42 |
| Belgium | 6,22 | Romania | 0,42 |
| Austria | 5,03 | Bulgaria | 0,28 |
| United Kingdom | 3,50 | Czech Republic | 0,28 |
| USA | 2,73 | Slovakia | 0,28 |
| Switzerland | 2,45 | Canada | 0,21 |
| Taiwan | 1,82 | Japan | 0,21 |
| Poland | 1,68 | Estonia | 0,14 |
| Norway | 1,47 | Israel | 0,14 |
| Portugal | 1,40 | Malta | 0,14 |
| Hong Kong | 1,12 | Singapore | 0,14 |
| Denmark | 1,05 | Tajikistan | 0,07 |
| Ireland | 0,98 | Turkey | 0,07 |

The number of unsold objects per year is uneven (Fig. 17) with several years having 96% of objects sold and others having only 71%.

In the unique case of Catawiki, 6,664 fossils were auctioned in 2022. This number exceeds the total number of fossils auctioned by all OAH (3807, with 3375 fossils sold) we considered over the 12-year period analysed. All the data are reported in Table 3.

The number of fossils sold at auction continues to increase. According to the data provided by the auction houses themselves on their official websites, which include both online and physical auctions, the number of OAH has risen in just over a decade from less than a hundred to more than 600 (a net increase of 60%). The authors are keen to point out that there may have been exceptional auctions that were not included on their websites and, in any case, private sales (transaction promoted by auction houses directly in between a seller and a buyer, without bid increases) of exceptional finds for exclusive clients cannot be included. There is no single reason for this: the greater ease with which collectors can find fossils, the publicity generated by documentaries, films and TV series, and the greater purchasing power on the part of collectors. The Internet has also played its part in this change. It is a fact that the Internet existed before the beginning of the period analysed in our article. However, it is necessary to consider that the hype surrounding certain fossils has been multiplied by social media. Auction houses, out of self-interest, tend to auction only item that can be likely sold and with a considerable earning for both the seller and them, and according to the percentages of unsold fossils analysed,

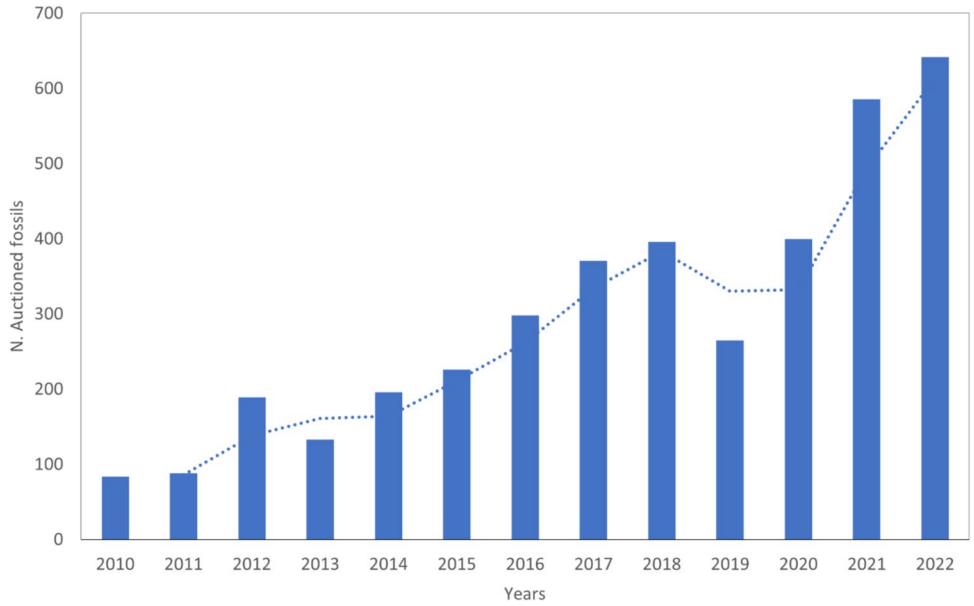


**Fig. 16** Number of fossils auctioned over time, without the data collected from the Catawiki auction house. The dotted line is the modal average

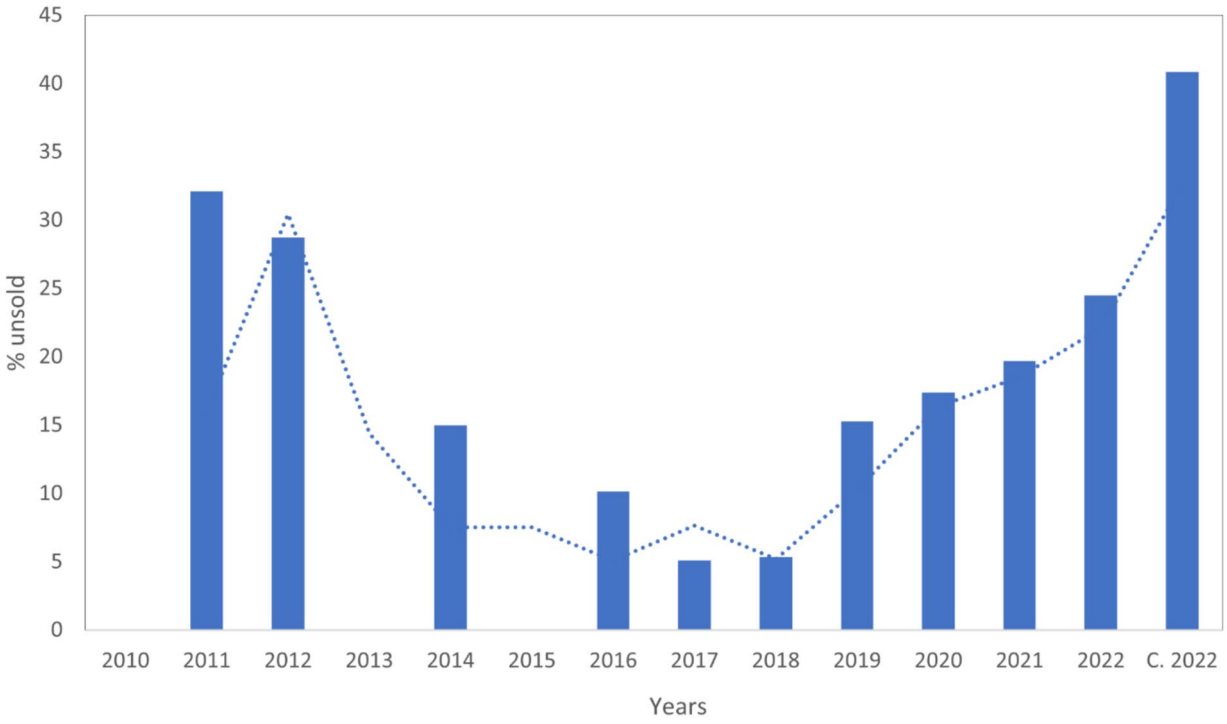


**Fig. 17** Percentage over time of unsold fossils (including data from Catawiki auction house, indicated as C.2022). The dotted line is the modal average

we can say that auction houses have a fair consideration of which fossils can be sold because they manage to sell most of the offered items (never exceeding 30% of unsold fossils per year). If we analyse the data excluding the auction house Catawiki, we can say that of the total number of fossils, 18% were unsold. If, on the other hand, we consider only the specific case of Catawiki, we can make different observations. Thanks to the peculiar marketing strategy of Catawiki (see below), the total number of its items auctioned is exceptionally high: in a single year it exceeds (almost double) the total number of fossils auctioned in 12 years by OAH. Whereas in the case of the other auctions the unsold fossils were less than 20% of the total of fossils presented, Catawiki in 2022 did not sell about 40% of the fossils presented. From this

**Table 3** Table showing the number of fossils auctioned, how many were sold and how many remained unsold, by OAH

| Date | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N° auctioned fossils | 84 | 88 | 189 | 133 | 196 | 226 | 298 | 371 | 396 | 265 | 400 | 586 | 642 |
| N° fossils sold | 84 | 62 | 136 | 133 | 170 | 226 | 271 | 354 | 377 | 229 | 340 | 484 | 509 |
| N° fossils unsold | 0 | 26 | 53 | 0 | 26 | 0 | 27 | 17 | 19 | 36 | 60 | 102 | 133 |
| Percentage of fossils sold | 100% | 70% | 72% | 100% | 87% | 100% | 91% | 95% | 95% | 86% | 85% | 83% | 79% |

we can deduce that Catawiki has a very different (and efficient) business plan because it offers at auction many more fossils than OAH, and instead of concentrating on a few fossils with potentially large profits, offers a large quantity of fossils (which can attract a larger and less selected audience), so that even if 40% of fossils remains unsold in a year the margin of profit is certainly satisfying. It is noteworthy that in the case of Catawiki the sellers do not ship the items to Catawiki office prior to the auction, but directly to the buyers. Sellers autonomously take care of providing photos of the fossils. This represents a significant simplification of the whole process, allowing the offer of items in a wide range of price.

Particularly informative are the cases of ammonites and dinosaurs because of the high number of items sold in the first group and the iconic and economic value of the latter. Analysing the auctioning of ammonites though time, it is possible to see a general decrease in their sale, but, at the same time, a selection by some auction houses of "museum quality fossils" that are constantly sold.

The number of unsold OAH dinosaurs is almost constant (0 to 4% unsold fossils per year), so more than 95% of the dinosaur fossils auctioned have been sold. The same reasoning does not apply to Catawiki, which "only" managed to sell 68% of the dinosaur fossils auctioned in the single year examined, a datum aligned to the general results reported above.

2020 and 2021 were special years due to the global Covid-19 pandemic, which brought most global economic activity to a halt. OAH, increased the number of fossils at auction, though the percentage of fossils sold remained constant. We found evidence (thanks to personal contacts) that many people started their collections during the pandemic, in particular through Catawiki. Because of the prolonged lockdowns they started using the Catawiki auction house as they had more time to spend online and found this type of auction a way to pass the time. Some sellers also started using the auction house at this time, as they were unable to go to their physical shops or attend trade fairs.

## Sale Prices and Estimates

The prices of the auctioned items were in most cases estimated by experts, but not all auction houses have experts who are familiar with Palaeontology. This might explain why in some cases the estimates had a very wide range (for example 1000–10.000 US dollars), whereas in few other cases (21%) the estimate is not even indicated. In 21% of the examined cases the final sale price was lower than the lower estimate, whereas in only 7% of cases it was higher than the higher estimation.

Considering the data for all fossil categories and all auction houses, 21% of the fossils were sold at a price that fell within the low and high estimate range. OAH and Catawiki present, however, different sale patterns. The OAH has 54% of the fossils sold at a price that is within the high and low estimates given by the in-house experts, and the fossils sold above and below the estimates have similar percentages (17% above the high estimate, 16% below the low estimate).

The evaluation of the economic value of the fossils offered for sale varies significantly between the auction houses grouped as OAH and Catawiki, as does the percentage of unsold fossils. At OAH, a direct expert evaluation of the object is always conducted. In France, in particular, it is required that the auctioneer be assisted by an independent expert, according to a special legal code (personal communication from Iacopo Briano). Large auction houses in other countries employ consultants or department heads who partly fulfil the role of experts. Catawiki utilizes experts to verify the information provided by the single seller through photographs and self-certifications, without requiring the material to be sent to the auction house. Catawiki is the only analysed auction house that allows sales to proceed even without an estimate, but always after remotely verifying the information and documentation provided by the seller.

Furthermore, the percentage of fossils sold by all auction houses at a price higher than the estimate for the four main groups of fossils analysed (ammonites, chondrichthyans, dinosaurs and plants) varies between 5% (chondrichthyans) and 9% (ammonites), while that relating to sales that realized a sum lower than the estimate varies between 16% (plants) and 27% (chondrichthyans).

The total fossils sold during the 12 years period analysed fetched 102.361.952 €. However, if we look at the data more closely, Catawiki handled transactions for 818.595 € in a single year (and remains one of the auction houses with the lowest buyer's premium at 9%), whereas the auction house

with the highest total amount of transactions was Christie's with 45.288.498 €.

As the data showed that dinosaur fossils are the most profitable, we focused our analysis on the following auction houses: Christies', Sotheby's and Heritage Auctions (Fig. 18 a-c). These auction houses have very different time trends in their revenues (Christie's and Sotheby's earn most from 2020 onwards, while Heritage Auction's peak was in 2011 and 2012), but there is a similarity: when a complete dinosaur is sold, it far outweighs all the revenues that can be obtained from the other fossils (although the latter are also important from an economic perspective if considered together). The Stan dinosaur is the most expensive dinosaur that has ever put on the market, and its sale alone accounts for 35.5% of the revenue for the entire period analysed, including all auctions. In fact, the graphs show that it is not the quantity of dinosaurs sold that drives the increase in revenue, but the presence of a single exceptional item. That shows that, in general, there is no quantitative correlation between the number of objects offered for sale and the auction house's revenue.

## Historical Case Studies

The buying and selling of fossils is not a recent activity, in fact we there is evidence of such transactions (and fraud) dating back to historical times. The ancient Egyptians, Greeks and Romans investigated the origin and provenance of fossil objects, although these cultures did not have our current concept of fossils. These peoples were already collecting, trading and buying fossils (Mayor 2011). Georg Bauer/Alias Agricola (1494–1555), Conrad Gessner (1516–1565) and Pietro Andrea Mattioli (1501–1578) are among the earliest possible collectors and scholars who may have acquired fossil specimens, mainly megalodon and ammonite fossils, for their collections and scientific studies (personal comment by Alessandro Ceregato). Ulisse Aldrovandi (1522–1605) also procured naturalistic specimens for his own collection (fossil and non-fossil) in many ways, including buying them, though often through a collaborator or patron: first and foremost the Medici, but also his cousin Pope Gregory XIII. We can find evidence of these purchases in the Aldrovandi manuscripts, which are being digitised by the University of Bologna (https://amshistorica.unibo.it/aldrovandi manoscritti). Another example that can be given is in the late 1700s, where a significant event occurred in Verona, Italy, which sparked a frenzy of fossil trading from Bolca lagerstätten. Notable figures such as Vincenzo Bozza, Serafino Volta and Giovanbattista Gazola made purchases from local people, leading to the creation of the '*Ichthyologia Veronese*' and the Gazola Museum. Despite setbacks such as Napoleon's confiscation, Gazola persevered and eventually bequeathed his collection to the Cerato family, who continue to exhibit and promote the study of Bolca fossils today.

Certainly, the recent advent of the Internet, media and movies led to the rise of this phenomenon, but one of the most famous (modern) auctions who attract media attention took place in the 1920's. The American palaeontologist Roy Chapman Andrews, after returning from an excavation campaign in Central Asia between 1921 and 1930, noticed that the dinosaur eggs brought back from the expedition were very famous, even more so than other important items. In order to raise funds for the second expedition, he decided to auction off one of the eggs, which not only proved successful but also attracted more public attention and donations. "Offers came from all over the world [… and …] the egg was sold to Colonel Austin Colgate for $5000 "(Andrews et al. 1933). However, this sale (especially the amount of money, which was very high for the time and especially for a scientific discovery) damaged relations between the American and Mongolian governments. According to Andrews, "the Mongolians suspected that the American team was making huge profits from the sale of the dinosaur eggs, and thus were discouraged from allowing foreigners to come in and rob the priceless possessions of the Mongolian people" (Yen 2015). Currently, Mongolia considers its fossils to be cultural heritage and the export of fossils to other countries as illegal (see https://www.aaps-journal.org/Mongolia-Fossil-Laws.html).

## Deaccessioning

Today, fossils arrive at auctions in a different way, no longer through scientific expeditions sponsored by universities and museums (see the case of Andrews briefly presented in the Introduction). An interesting and controversial phenomenon is the deaccessioning of museums' collections. This word indicates the intention of a museum to get rid of some of the items in its collection through sale or exchange (Callery 2002). Deaccessioning is a controversial practice, however, which has also led to bad publicity for museums that have decided to implement it, such as the New York Historical Society, the Historical Society of Pennsylvania and the Shelburne Museum (Demouthe et al. 2000). There are many reasons for which a museum might make this choice: lack of space, lack of knowledge and scientific uselessness of an item, lack of funds for other acquisitions needed by the museum, the need for exchanges with other institutions, even the payment of staff salaries (as in the case of the Glenbow Museum described by Ainsle in 1996). The sale may have been carried out directly by the museum institutions, or sometimes they even relied on auction houses to sell their fossils (Demouthe et al. 2000). As far as fossils are concerned, worth mentioning is the case of the San Diego Museum, which auctioned fossils in 2013 in order to have the opportunity to acquire additional finds more relevant to its collection. At this auction, a fossil collected in the past by Charles Sternberg was sold following all the

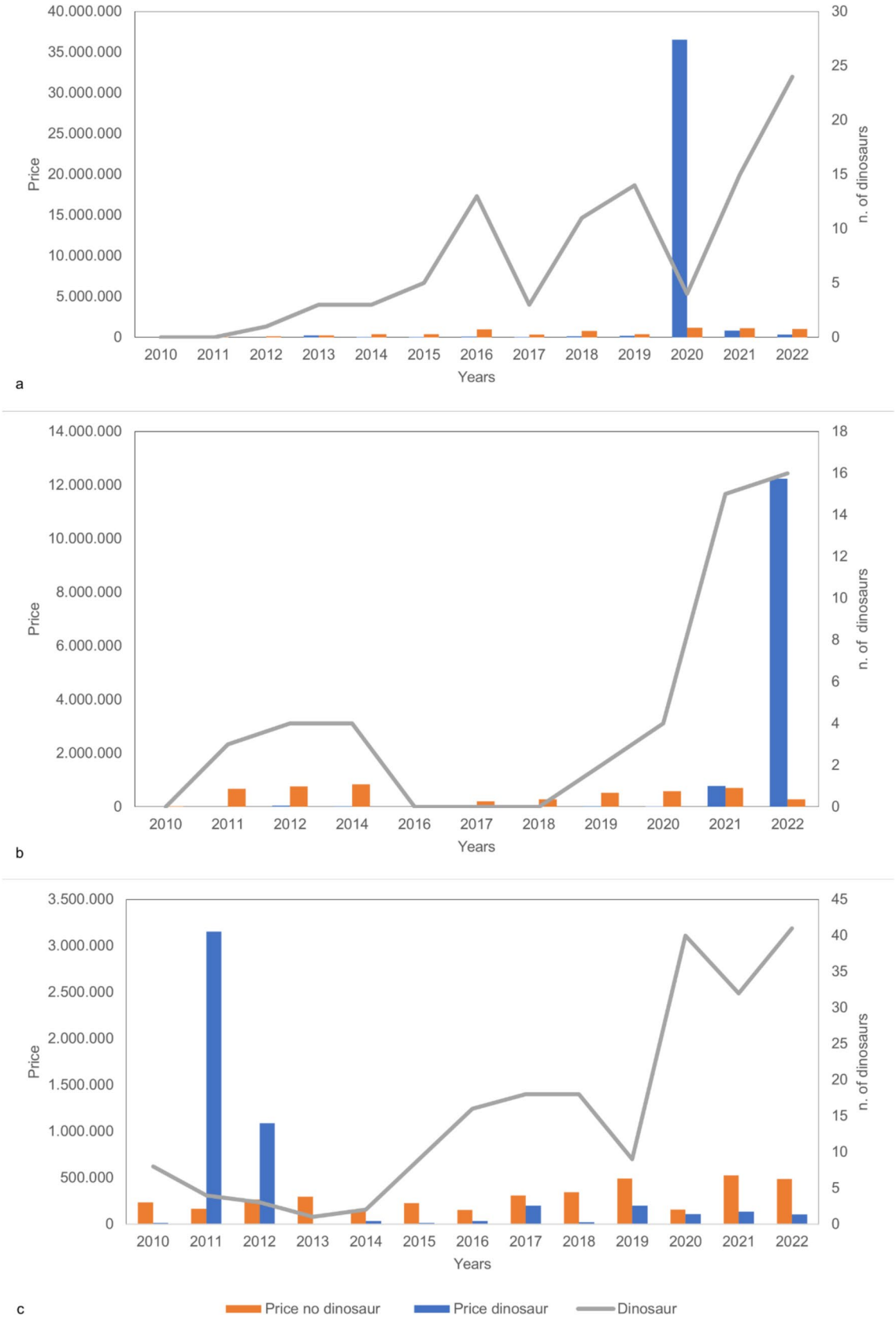


**Fig. 18** Correlation between price of dinosaurs, price of all other fossil auctioned and number of dinosaurs auctioned over the time for some Auction Houses: **a** Christies', **b** Sotheby's, **c** Heritage Auctions

deaccessioning guidelines set out by the American Alliance of Museums (AAM) (see the museum's blog, https://www.sdnhm.org/blog/blog_details/fossil-deaccession/8/).

With regard to auction sales, we have to bear in mind that "Usually … something … is sold [at auction] because of the three D's: death, divorce or debt, or because collectors' tastes have changed" (Adams et al. 2017). This applies to all artefacts sold at auction, and fossils are no exception. It should be remembered that in the past, the aristocracy and upper middle class loved to surround themselves with special and curious objects, creating veritable Wunderkammer to entertain their guests; as a result, even objects that were once 'legitimately' collected have been passed down from generation to generation to the present day. Cases in which fossils are sold directly by state museums or palaeontologists working for research centres and universities are rare nowadays, but this does not mean that all the items, once purchased, will stay forever in a single collection.

## Dinosaurs and Museums

The first large complete dinosaur to be sold at Sotheby's New York auction of October 1997 and cause a sensation was Sue (FMNH PR 2081). This tyrannosaur was discovered by Sue Hendrickson while working at a site near Faith, South Dakota, "with a commercial fossil collecting team from the Black Hills Institute" (Makovicky 2000). Sue, after having seized by the Federal Bureau of Investigation, has been "auctioned and purchased for over $8 million by the Field Museum of Natural History with financial support from the McDonald's and Disney Corporations" (Jones 2018). Sue is the largest, most complete and best-preserved *Tyrannosaurus rex* in the world, has been thoroughly studied by scientists (among others Brochu 2003). Sue has also been used for numerous casts, allowing visitors from all over the world to see an exceptional specimen with their own eyes. However, we must not forget the negative legal vicissitudes associated with this purchase (for a more in-depth look at this topic, see Wolberg and Reinard 1997, pp. 52–55).

To make a comparison with another recently sold *Tyrannosaurus rex* (and included in our database), we need to bear in mind that Stan *Tyrannosaurus rex* was sold by Christies' New York auction in October 2020 for around $31 million. At first it was not known who the buyer was, and there was much speculation in the press and on social media, including that the mystery buyer was Dwayne 'The Rock' Johnson (e.g. Gamillo 2022). It was later revealed that the real buyer was the Department of Culture and Tourism of Abu Dhabi, which was commissioned to buy the famous *T. rex* for the Natural History Museum in Abu Dhabi, capital of the United Arab Emirates (e.g. Greshko 2022) and therefore for being put on public display.

Another example is Big John, a *Triceratops horridus* skeleton (Fig. 19), which was sold by Binoche et Giquello at Hotel Druot (Paris) in 2021 for 6.8 million euros, and

**Fig. 19** *Triceratops horridus* "Big John". ©Giquello

whose new owners have made it available for a three-year exhibition at the Glazer Children's Museum in Tampa (USA). The motivation for this collaboration is clearly described by Pagidipati Siddhartha, Big John's owner, on the website dedicated to the event: “Ever since I was a young boy, I have been fascinated by the dinosaurs that roamed the earth. […] Now everyone will have the chance to see him in person and experience what his world was like 66 million years ago” (Pagidipati 2022). This American fossil was purchased and exported to Italy by the company Zoic srl., which, before participating in the sale of the fossil, had prepared it, promoted its scientific study (D'Anastasio et al. 2022), collaborated in the writing of an educational book, as well as used it as a source of entertainment for the entire city of Trieste in one of the major square with a temporary exhibition (July – August 2021) of the fossil.

The latest example of a *Tyrannosaurus rex* sold at the Kooler’s auction (in Zurich) is Trinity, so called because it consists of the remains of 3 different specimens, also from different localities (Hell Creek and Lance Creek formations in Montana and Wyoming). Although it appears to be a 'collage', it has achieved a very high economic value of approximately 5.5 million Swiss Francs. This specimen was purchased by the Phoebus Foundation, which has made it possible for the Boerentoren Cultural Center in Antwerp (in Belgium) to exhibit it. Although this fossil is not scientifically very relevant (being a compiled skeleton), it is an undeniable testimony of the past and will therefore be shared with all citizens. In addition, since 2023, the Kooler auction house, which sold this fossil, in collaboration with the Wunderkammer Zurich, has been running a campaign to make palaeontological items more accessible to scientific research. The project is called ASTRA (Advancing Science Through Research Availability) and consists of professionally 3D scanning fossils and making them available for free download to museums, palaeontologists and enthusiasts.

However, it should be remembered that selling fossils at auction at exorbitant prices means a price increase that prevents them from being purchased by small and medium-sized museums. Moreover, pieces sold at auction can also be considered 'disruptive objects' (Yates and Peacock 2023), as in the case of the *Tyrannosaurus rex* Shen, which was withdrawn from Christie's Hong Kong auction in 2022 after doubts were raised about the amount of authentic bones. In any case, the New York exhibition of this fossil has been a huge success (Yates and Peacock 2023), and it has been the first 'complete' dinosaur to be sold at auction on the Asian continent, attracting both public and academic interest.

## Final Remarks

The results of this study demonstrate that monitoring the fossil auction market provides valuable data for understanding the types of fossils available on the globlal market. This includes trade shows, physical stores and auction houses, catering to individual collectors, as well as research institutions and museums, seeking to enrich their collections. Additionally, it offers insights into the real value of fossils for insurance purposes. The fossil trade is expanding both quantitatively and economically, with fossils commanding unprecedented prices, and auction houses attracting more collectors than ever before. This trend is expected to continue. While this development allows all enthusiasts to acquire a “piece of the past”, it also raises concerns regarding the legality, ethics, and the potential impact on scientific research and preservation efforts. This study shows the existence and global dimension of the fossil market. Collaboration between private and public institutions is likely one of the ways to implement greater control and protection of the paleontological material that is scientifically important. Only through clear, easily applicable, and shared regulations trade could be regulated for the protection of paleontological goods without criminalizing the legal trade of fossils.

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## Declarations

**Competing Interest** The authors declare no competing interests.

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